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Global sale of green air travel supported using biodiesel†

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Abstract

The technical feasibility of operating commercial aircraft on low concentration biodiesel in kerosene blends is reviewed. Although the analysis is preliminary, it seems plausible that a biodiesel component could be introduced without significant modification to aircraft, airport infrastructure, and flight operations.

The use of a biodiesel component, even for only a subset of flight operations, would open the possibility of giving all passengers, the world over, regardless of route, the option to pay a premium to make their journey on "green" fuel (actually biodiesel). In this way, the airline industry could recover the additional cost of biodiesel in comparison to kerosene. The costs associated with such a scheme are estimated, as is consumer demand. Although the analysis is preliminary, the scheme appears commercially viable.

From a humanitarian and/or environmental perspective, marketing flight on biodiesel as "green air travel" is problematic. On the one hand, the use of biodiesel in aviation would reduce addition of carbon dioxide to the atmosphere and foster development of sustainable technology. On the other hand, it would require that agricultural resources be dedicated to air travel, nominally a luxury, in a world where agricultural resources appear destined to come under increasing strain merely to satisfy humanity's basic food and energy needs. A preliminary discussion of these issues is presented. It is hoped that this can serve as the starting point for further discussion, at an international level, to reach consensus on whether marketing of flight on biodiesel as "green air travel" should be allowed to proceed, or whether it should be declared unethical.

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† A web page devoted to this topic will be maintained at http://www.phy.auckland.ac.nz/staff/daw/

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Keywords: Alternative fuels; Aviation turbine engines; Fuel temperature; Green marketing; Sustainable development; Agricultural and energy resources; Population; Personal transportation; Green electricity; Consumer demand

Contents

General notes: In this document, one billion is equal to one thousand million. US means United States. EU means European Union (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom). Dollars and cents refer to US currency. Gallons are US gallons. Tons are metric tons (i.e. 1 ton = 1000 kg). “B5Jet” refers to a 5% (by volume) blend of biodiesel in kerosene. In preparing the document, it was sometimes necessary to convert between energy units. For this purpose, one barrel of oil has been assumed to have an energy content of 6.2 GJ. So a barrel of oil equivalent (BOE) is an energy resource, for example, coal, with an energy content of 6.2 GJ. Other conversion factors used: 1 barrel = 42 gallons, 1 gallon = 3.785 litres, 1 lb = 0.454 kg, 1 Btu = 1054 J. The web addresses cited in the footnotes and references were accessed between April and November, 2002.

1. Introduction/summary

The world’s airliners are currently fuelled using kerosene, which is derived from fossil fuels, in particular, crude oil. Biodiesel is a fuel with similar properties to kerosene but is derived either from vegetable oil or animal fat. Unlike fossil fuels, biodiesel can, in principle, be produced and consumed indefinitely, and its use need not irreversibly add carbon dioxide to the atmosphere.

The purpose of the present paper is to raise the possibility of:

P1 Fuelling the world’s airliners, mainly using kerosene, but with a small biodiesel component.
P2 Giving passengers the opportunity to specify, and pay for, the mix of fuels (pure kerosene, pure biodiesel, or some mixture of the two) on which they fly.
P3 Marketing flight on biodiesel as green air travel.

Note that this possibility has many similarities with the marketing of electricity gen-

erated using sustainable technologies (such as wind power) as “green” electricity (or “green” power), which is already taking place in some parts of the world.

The organization of the paper is as follows, with some relevant statistics for the airline industry being included in Appendix A.

Section 2 discusses the technical feasibility of fuelling some commercial airline flights using low concentration (not exceeding 5% by volume) blends of biodiesel in kerosene, while retaining pure kerosene on other flights, such that the airline industry, as a whole, is fuelled using a small percentage of biodiesel (perhaps 1%), with the remainder being kerosene. The use of biodiesel blends raises a number of engineering issues, such as whether there is a risk of fuel freezing on board aircraft flying at altitude. The section aims to identify such issues and give a preliminary assessment of their significance. On some points, further investigations are required. Nevertheless, the preliminary assessment suggests the following conclusions:

1.1 The introduction of biodiesel would require, at most, only minor modifications to existing aircraft and airport infrastructure.
1.2 The introduction of biodiesel would have negligible impact on flight operations (for example, refuelling time on the ground, range/payload characteristics of aircraft).
1.3 The presence of biodiesel in the fuel would not significantly alter aircraft exhaust emissions.
1.4 The presence of biodiesel in the fuel would not alter the ride experienced by passengers (aircraft would fly at the same speed, make the same amount of noise, and so on).

The purchase of an airline ticket is, in part, a fuel purchase. At the present time, when a passenger purchases an airline ticket, the airline industry purchases a quantity of kerosene on the passenger’s behalf, and loads it onto the passenger’s plane for use during the passenger’s flight.

The use of kerosene in commercial aviation raises a number of social and environmental concerns. These are discussed in Section 3. The use of biodiesel, in place of kerosene, addresses at least some of these concerns. As a consequence, some passengers may be prepared to pay an increased fare so that the airline industry can purchase a quantity of “green fuel” (in reality, biodiesel), in place of the more usual kerosene (biodiesel is more expensive than kerosene).

The airline industry could load the biodiesel paid for by a passenger onto the passenger’s plane for consumption during the course of his/her flight. However, this is not really necessary, as the passenger receives the same benefit, regardless of which flight the biodiesel paid for by the passenger is used on. This is true for two reasons. Firstly, the ride experienced by the passenger is unaffected by the presence or absence of biodiesel on their flight (see Conclusion 1.4). Secondly, the concerns listed in Section 3, do not centre specifically on the passenger, but rather impact equally across very large communities. As an example, the use of kerosene irreversibly adds carbon dioxide to the atmosphere, and the carbon dioxide spreads across the whole globe. Because the concerns impact across such large communities, the

concerns are equally mitigated, and the passenger receives the same benefit, regardless of which flight the biodiesel paid for by the passenger is used on. In particular, it could be used on a flight operated by a different airline, flying a different route, at a different time. This suggests a scheme in which airlines operating aircraft on biodiesel/kerosene blends could generate "green air miles" for sale to other airlines. In this way, passengers across the entire globe could be given the opportunity of flying on "green fuel", even if the airline with which they wish to fly does not use biodiesel on the route they wish to travel. The scheme is similar to the trade in green energy certificates which already occurs in some deregulated electricity markets, and is described more fully in Section 4.

From the point of view of the airline industry, it might be desirable to encourage passengers to pay to fly on "green fuel" (this would, for example, help protect the industry from concerns over global climate change). Section 5 presents a simple, low cost, strategy that the airline industry could, if it wished, use to make all prospective passengers aware they had the option of flying on green fuel.

Sections 4 and 5 include estimates of administrative and marketing costs. The actual price passengers will pay to fly on "green" fuel is calculated in Section 6.

Once the price premium for green air travel is known, the demand for green air travel can be estimated, using experience with the sale of green electricity as a guide. This is done in Section 7.

The preliminary analysis of Sections 4–7 suggests the following conclusions:

1.5 It would be straightforward to extend choice of fuel mix to all passengers across the whole globe, and also to make all passengers aware they have a choice of fuel mix.
1.6 The cost involved in Conclusion 1.5 would be completely negligible in comparison to total passenger revenues, and could therefore be funded from an across the board levy on all airfares, with no discernible fare increase for those passengers who elect to fly on 100% kerosene.
1.7 Assuming no government subsidies, the cost to passengers of flying on 100% green fuel would be approximately 9% greater than flying on pure kerosene for regional flights, and approximately 27% greater for intercontinental flights.
1.8 Following the introduction of fuel choice, sales of green air travel would grow, then equilibrate at between 0.1% and 1% of total air travel. The time required for equilibrium to be reached would be comparatively short (a matter of months, rather than years).

Given that introducing fuel choice would cost the airline industry a negligible amount in comparison to its revenue (Sections 4 and 5), and that it would allow the industry to secure 0.1% to 1% of its passenger revenue (representing between 0.24 and 2.4 billion dollars annually) from concerns surrounding the use of fossil fuels (Section 7), it would seem likely that the airline industry would need no encouragement to introduce fuel choice, and would do so of its own accord, assuming the technology (Section 2) allows it. This raises the following question:

Is it legitimate for flight on biodiesel to be marketed as “green” air travel?

It is imperative that the global political community debates this question, and then gives a clear yes/no answer.

Section 8 gives further background regarding this question. Naively, flying on biodiesel might seem a simple matter of substituting kerosene, a nonrenewable, carbon dioxide increasing fuel, with biodiesel, a renewable, carbon dioxide neutral fuel, and therefore consistent with “green” objectives. However, the production of biodiesel diverts agricultural land from food production, and therefore flight on biodiesel could undermine global food security. The analysis in Section 8 suggests that, if all the world’s people are to be substantially freed from the hardships of undernutrition, disease, and war (which would seem part of the green agenda), then transportation should continue to be fuelled using petroleum, rather than biofuels. In addition, there would seem a need to redirect human resources from developed to less developed nations, and a need for individuals to limit their total travel (excluding walking, bicycling, etc.) to, on average, less than 8000 km per year. If these conclusions are correct, then marketing flight on biodiesel as “green” would be inappropriate, as it would give prospective passengers the impression they could consume any quantity of air travel without compromising “green” objectives, regardless of the purpose of their journey (whether they were travelling as part of the redirection of human resources from developed to less developed nations), and regardless of whether the journey was within their travel allowance (of, on average, less than 8000 km per year). However, the goal of eliminating undernutrition, disease, and war may be unrealistic, and, if that is the case, the introduction of flight on biodiesel, and its marketing as green air travel, might prove a useful tool in reducing the dependence of the developed world on non-sustainable technology. These issues are clearly complex, and hence the need for a global debate, to either approve the introduction of a potentially useful tool to promote sustainable development, or to block a potentially dangerous scheme that could undermine global food security.

2. Technology

As will be discussed in Section 7, if choice of fuel (kerosene, “green fuel”, or some mixture of the two) was introduced, and, if flight on green fuel was marketed as environmentally and socially benign, demand for flight on green fuel could be as large as 1% of all air travel sold. As will be discussed in Section 6.1, in order to meet this demand, the airline industry, taken collectively, would have to substitute ~1.5% of the kerosene it currently uses with biodiesel (although there would be no restriction as to how much biodiesel would need to be used on any particular flight). The technically simplest way of achieving such substitution is probably to operate some flights on low concentration blends of biodiesel in kerosene, perhaps not exceeding 5% biodiesel by volume, while continuing to operate other flights on pure kerosene. The purpose of the present section is to assess the technical feasibility of this approach.

At most modern airports, fuel is available at each terminal gate, delivered by a network of underground pipes. One possibility for the introduction of biodiesel would be to continue to operate the network on pure kerosene, but have biodiesel available from a mobile tanker, as shown in Fig. 1. The tanker would carry pure biodiesel. During refuelling, pure kerosene would flow from the underground piping into the tanker. A mixing unit would add biodiesel in the required proportion, and the resulting fuel mixture would then be pumped aboard the aircraft. If, for whatever reason, the aircraft was to be fuelled with pure kerosene, the tanker needn't be employed, and the aircraft could be refuelled directly from the underground piping, as is currently usual. This scheme would be compatible with all existing airport infrastructure, which only leaves the issue of operating the aircraft themselves on biodiesel/kerosene blends.

2.1. Kerosene and biodiesel

Currently, fuel for aviation turbine engines is extracted from fossil resources, primarily crude oil. Molecules in the fuel are hydrocarbons, with a typical molecule containing between 9 and 16 carbon atoms [1] and approximately twice as many hydrogen atoms. The exact mix of molecules depends both on the origin of the crude oil and on the extraction process. This leads to fuels with different properties. Three fuels are widely recognized for use in commercial aviation turbines; Jet A, Jet A-1 (both referred to as aviation kerosene) and Jet B (referred to as wide-cut fuel). All three fuels are defined by American Society for Testing and Materials standard ASTM D 1655 [2]. Jet A has a maximum freezing point of −40 °C and accounts for almost all the fuel distributed through US airports.[1,2] Jet A-1 differs from Jet A

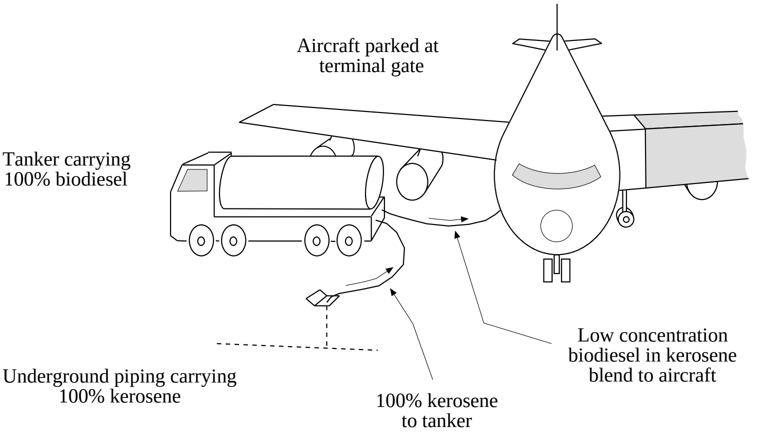

Fig. 1. Refuelling an aircraft with a low concentration biodiesel in kerosene blend.

[1] Bureau of Transportation Statistics, US Department of Transportation.
[2] Private Communication, Information Service Staff, (footnote 1) (e-mail: Answers@bts.gov).

only in freezing point (maximum of −47 °C), and, with a few exceptions, accounts for all the remaining fuel distributed through non-US airports around the world. Jet B is a more volatile fuel, having a greater fraction of low molecular weight hydrocarbons, and is of only limited use in civil aviation. Jet A-1 and Jet B also have US military equivalents, referred to as JP-8 and JP-4, respectively.

Biodiesel is one product of the chemical reaction of an alcohol with a vegetable oil or animal fat (the other product being glycerol). In this paper, the alcohol is assumed to be methanol. Biodiesel is then a mixture of methyl esters of different fatty acids. A typical biodiesel molecule contains between 13 and 23 carbon atoms, approximately twice as many hydrogen atoms, and two oxygen atoms. Note that the molecules in biodiesel are very similar to the molecules in kerosene, and, from the point of view of chemistry and physics, the two fuels are similar in all respects.

A more complete account of the information presented in this subsection can be found in [3–5].

2.2. Experience with biodiesel as an automotive fuel

Biodiesel has been in use for some years as a fuel for trucks and buses. In the US, the total consumption for the year 2000 was approximately twenty million gallons.[3] A 20% biodiesel/80% fossil diesel blend (called B20) can be used in any diesel engine vehicle, regardless of age, without any need for modification (although, in a small minority of cases, rubber hoses and seals perish and must be replaced). The use of this fuel even has a number of technical advantages. It prolongs engine life and reduces the need for maintenance (biodiesel has better lubricating qualities than fossil diesel). It is safer to handle, being less toxic, more biodegradable, and having a higher flash point. It reduces some exhaust emissions (although it may, in some circumstances, raise others [6]). The technical disadvantages of biodiesel/fossil diesel blends include problems with fuel freezing in cold weather, reduced energy density, and degradation of fuel under storage for prolonged periods. One additional problem is encountered when blends are first introduced into equipment that has a long history of pure hydrocarbon usage. Hydrocarbon fuels typically form a layer of deposits on the inside of tanks, hoses, etc. Biodiesel blends loosen these deposits, causing them to block fuel filters. However, this is a minor problem, easily remedied by proper filter maintenance during the period following introduction of the biodiesel blend.

A more detailed discussion of the information presented in this subsection can be found in reference [4] and footnote 4.

[3] Private communication, K. Shaine Tyson, Renewable Diesel Project Mgr, National Renewable Energy Laboratory (k_shaine_tyson@nrel.gov), May 2002.

[4] Biodiesel-Clean, Green Diesel Fuel. DOE/GO-102001-1449, National Renewable Energy Laboratory, US Department of Energy, Sept 2001 (http://www.afdc.doe.gov/pdfs/Bio_CleanGreen.pdf).

2.3. Preliminary experience with aviation turbines

That aviation turbine engines will operate satisfactorily on low concentration biodiesel in kerosene blends, has already been demonstrated by two groups of researchers, one at Purdue University [7,8], and one at Baylor University [9].

The Purdue group investigated the biodiesel, soy methyl ester (SME). Their investigations encompassed both laboratory testing of fuel properties and ground operation of an aircraft engine fuelled with 2% and 20% SME in Jet A blends. The engine used for the testing was a Garrett TPE-331-3U-303V turboprop, fitted to the wing of a Handley Page HP.137 Jetstream 1. The engine was not modified in any way for the testing. When operated on blend, the engine turbine temperature, fuel pressure, and fuel flow were all normal, and the engine started and operated normally. The group also measured engine exhaust gas emissions at idle and medium power, and fuel consumption at medium power.

The Baylor group have operated a Pratt and Whitney PT6A-6 turboprop engine, held in a ground test stand, on a number of biodiesel/Jet A blends, with biodiesel from both vegetable and animal sources, and concentrations of biodiesel in Jet A as high as 30% by volume. The group have also performed flight tests using a Beachcraft King Air A90 with one of its two PT6-20 turboprops fuelled using a 20% by volume biodiesel in Jet A blend. Neither the PT6A-6 nor the King Air A90 were modified in any way, and no difficulties were encountered during any of the tests. In the case of the flight testing, the pilot could not discern any difference between operation on Jet A and operation on biodiesel blend, including in terms of aircraft performance and fuel economy. The Baylor group also measured engine exhaust emissions.

Laboratory measurements of biodiesel/kerosene blend properties have also been made by Dunn [10].

2.4. Appraisal of fuel properties

2.4.1. Density and net heat of combustion

The density and net heat of combustion[5] are important parameters in determining the performance of any aviation fuel. The ASTM standard [2] for Jet A/Jet A-1 specifies a density, at 15 °C, in the range 775–840 kg/m^3, and a net heat of combustion not less than 42.8 MJ/kg. For kerosene fuels, net heat of combustion is found to be approximately correlated with density. The correlation is summarized in Table 1 (see also Fig. 3 in [3]). Also shown in Table 1 are typical values of density and net heat of combustion for unblended biodiesel (see footnote 4) and calculated values for a 5% (by volume) blend of biodiesel and medium density aviation kerosene (referred to, for convenience, as “B5Jet”). The calculations assume that, when the

[5] This is also referred to as *lower heating value* (see http://www.ott.doe.gov/biofuels/glossary.html). It is defined as the quantity of heat released when a unit mass of fuel is combusted at a constant pressure of 1 atmosphere, with the water remaining in the vapour state. See also [3].

Table 1
Density and net heat of combustion of five fuels. Also, volumes and masses of samples with the same energy as 1 m^3 of medium density aviation kerosene

Fuel		Aviation kerosene			Biodiesel	B5Jet
		Low density	Medium density	High density		
Density at 15°C, kg/m^3		775	807	840	878	811
Net heat of combustion, MJ/kg		43.5	43.23	42.9	37.14	42.9
Samples of equal energy	Volume, m^3	1.035	1	0.968	1.070	1.003
	Mass, kg	802	807	813	939	813

biodiesel and kerosene are blended, there is no change in the volume occupied by a molecule and no change in energy. These are reasonable assumptions considering the large number of atoms in each molecule, the similarity of the molecules, and the lack of any chemical reaction between them.

Also shown in Table 1 are the volumes and masses of samples of all five fuels which contain the same energy as 1 m^3 of medium density aviation kerosene. Note that the volume and mass of the B5Jet sample are within the range of volumes and masses for the aviation kerosene samples. With regard to density and net heat of combustion, the use of B5Jet would therefore have negligible impact on aircraft operations (for example, range and payload carried). This conclusion is supported by the experiences of both the Purdue and Baylor groups [7–9]. In addition, in Section 6.2.3 it will be shown that the slightly increased mass of the B5Jet sample would have a negligible impact on airline operating costs.

2.4.2. Freezing point

Dunn [10] has measured the cloud point (which is related to the freezing point) of pure JP-8 and a blend of 10% (by volume) SME in JP-8, and found the results to be −51 °C and −29 °C, respectively. Based on experience blending SME and No. 1 diesel fuel (D1), from which jet fuels are refined, Dunn[6] predicts that the cloud points of 1% and 5% (by volume) SME in JP-8 would be no higher than −45 °C and −35 °C, respectively. Upper estimates for the maximum freezing point of aviation kerosene/SME blends are then anticipated to be as shown in Fig. 2.

The freezing point of fuel is a property of interest because aircraft flying at altitude can encounter low temperatures, and it is important that the fuel on board the aircraft does not freeze (freezing could impede the flow of fuel to the engines, causing engine failure). See, for example, the discussion in reference [3].

At the present time, the data available in the literature on fuel temperature during flight, appears to be quite limited. Pasion [11] has reported data for the B747, B707,

[6] Private Communication, R.O. Dunn, USDA Agricultural Research Service (dunnro@ncaur.usda.gov).

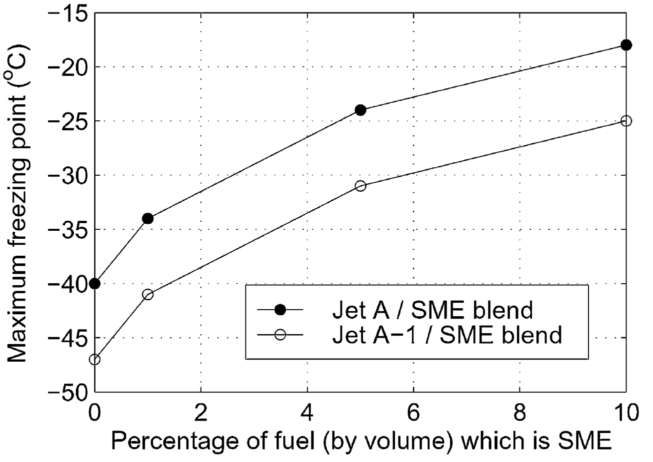

Fig. 2. Upper estimates for the maximum freezing point of aviation kerosene/soy methyl ester (SME) blends.

DC-10 and DC-8, flying on 12 different routes, during the northern hemisphere winter. The spatial profile of the temperature of the fuel within the tank of an L1011 has been reported by Svehla [12]. Most recently, data has become available on the minimum temperature reached by the fuel on board aircraft flying the new polar routes [13].

The data in references [11–13], is all for comparatively large, jet aircraft. To supplement this data, some data was obtained for flights with a smaller jet (a Boeing 737-300), and also with a regional turboprop (a Saab 340A) (see Appendix B).

On the polar routes, the temperature of the fuel can approach the freezing point of Jet A (and even of Jet A-1) [13], and it would not be possible to fly these routes on a biodiesel in Jet A or Jet A-1 blend. However, the minimum temperature reached by the fuel depends strongly on the flight operation. For example, in Pasion's data, given an aircraft type and route, the minimum fuel temperature recorded clearly varies from flight to flight by at least +/−5 °C (unfortunately the data gives no insight into how predictable such fluctuations might be). Also, although the minimum temperature for a DC-8 flying the North Atlantic was predicted to be as low as −46 °C, the corresponding figure for a DC-10 flying the Pacific was only −27 °C. The minimum fuel temperatures in Appendix B are also well above the freezing points specified for Jet A/Jet A-1, being approximately −15 °C and −5 °C for the B737 and Saab 340, respectively.

That the minimum fuel temperature for some flight operations is considerably above the freezing point specified for Jet A/Jet A-1, suggests the following scheme for aircraft refuelling: The flight crew would indicate to the ground crew the minimum fuel temperature anticipated for the flight. The ground crew would then load the aircraft with a blend of biodiesel in kerosene (see Fig. 1) with a freezing point not exceeding the temperature specified by the pilot (less a suitable safety margin).

In order for this scheme to succeed, flight crews would need to be able to predict,

with some certainty, the minimum fuel temperature expected for a flight. This could be achieved if minimum fuel temperatures were routinely recorded, and the information relayed to air traffic control. Air traffic control could then advise a flight crew on the minimum fuel temperature they might expect for a particular flight, based on experience gained by crews flying similar planes on the same or adjacent routes in the recent past. In this regard, it is relevant that many modern aircraft do have a temperature gauge for the fuel tank [13,14],[7] and that, potentially, avionics could be used to make the temperature measurements, avoiding distraction of the flight crew during flight.

As a safeguard, the ground crew could measure the freezing point of the blend, as it was loaded onto the plane (see Fig. 1), and relay the result back to the flight crew. The instrumentation required to make such measurements is already available at a modest cost and such freezing point measurements are already made for flights embarking on polar routes [13].

It therefore seems likely that freezing point will not impede the introduction of biodiesel in low concentration blends. Furthermore, there are other techniques, already developed, that could be used to lower freezing points, if required, such as treatment of the biodiesel before blending [10] (see also [4]).

2.4.3. Compatiblity of fuel with aircraft materials

In order to be used as a fuel, it is important that biodiesel blends are compatible with the materials used in construction of aircraft fuel systems, for example, that they do not corrode aluminium alloys, or cause seals and hoses to perish.

The Purdue group have already demonstrated that pure biodiesel perishes the nitrile rubber, Buna-N, which was common in older aircraft systems [7,8]. Despite this, there remains reasons to be optimistic that low concentration biodiesel blends will prove compatible with aircraft fuel systems:

- B20 shows a high level of compatibility with automotive fuel systems (see Section 2.2).
- If problems arose with seals or hoses, it might be inexpensive and straightforward to replace them with equivalents made from biodiesel resistant materials.
- The Baylor group have already operated an aircraft on a 20% (by volume) blend of biodiesel in kerosene without experiencing any problems [9].

With regard to the last point, the aircraft used by the Baylor group had lined tanks, while most modern commercial aircraft have integral tanks. Investigating the compatibility of low concentration biodiesel blends with the materials used to seal integral tanks would therefore be a priority for further research [9].

[7] Fuel tank temperature gauges are less common on small turboprops, for example, from among Air New Zealand’s fleet, the Saab 340A (33 seats) has one, while the Fairchild Metro III (19 seats) does not (see footnote 42). However, the data in Appendix B, also suggests fuel freezing is of least concern on smaller turboprops.

2.4.4. Thermal stability

In an aviation turbine engine, the pipes through which the fuel flows are typically hot. There are at least two reasons for this. Firstly, the pipes may be deliberately routed through hot parts of the engine, so that the flowing fuel can act as a coolant. Secondly, the pipes terminate with spray nozzles in the (very hot) combustion chamber. If the fuel is thermally unstable, solid deposits will accumulate on the internal walls of these pipes. Such deposits can impede heat transfer and foul spray nozzles [3].

As yet, there is no data on the thermal stability of biodiesel/kerosene blends, and this does represent a concern as biodiesel is known to be less stable than ordinary diesel fuel [15]. However, there is also reason for optimism, as, in some cases, additives can be used to raise thermal stability, if required [3,15,16].

2.4.5. Combustion properties

Dunn [10] has verified that the flash point of 10% (by volume) SME in JP-8 meets the ASTM D 1655 flash point specification.

Macmillan [17] has determined that ease of cold start (and presumably therefore also ease of altitude relight) is primarily determined by fuel viscosity. Dunn [10] has already demonstrated that even a 10% by volume SME in JP-8 blend had a viscosity at -20 °C only 16% above that of pure JP-8 (which satisfied the ASTM D 1655 standard).

The viscosity and surface tension of hot fuel are also important in determining the performance of a turbine engine, as they determine the characteristics of the fuel spray produced by the fuel spray nozzles. As yet, there is no data available for biodiesel/kerosene blends, but the fact that unmodified engines have operated successfully on blends with concentrations of biodiesel as high as 30% (by volume) [9], is encouraging.

The amount of thermal radiation produced when fuel is burnt is also an important parameter, as it determines the temperature of metal components in the combustion chamber of the engine. The amount of thermal radiation is strongly correlated with soot formation [3]. As yet, the amount of soot produced by the combustion of biodiesel/kerosene blends appears not to have been quantified. However, there is some evidence in both the Purdue and Baylor studies [7–9], that the addition of biodiesel to kerosene decreases soot formation.

The sulphur content of biodiesel (see footnote 4) is well within the ASTM D 1655 specification.

Because biodiesel and kerosene molecules are similar (see Section 2.1), the combustion of biodiesel/kerosene blends is expected to produce exhaust gases similar to the combustion of pure kerosene. To a large extent, this hypothesis has already been confirmed by the Purdue and Baylor groups [7–9], who made measurements of engine exhaust emissions. The use of low concentration biodiesel in kerosene blends is therefore unlikely to have any impact (positive or negative) on the ground level air pollution found in the vicinity of some airports.

2.4.6. Other issues

The Purdue group [7,8] raised concerns over the total acid number and existent gum of their biodiesel/kerosene blends. However, their total acid number was within ASTM D 1655 specification (whether the existent gum was within specification is unclear, due to an apparent typographical error in their paper). Also, these two parameters are expected to depend on the chemical processing used to obtain the biodiesel from the animal fat or vegetable oil. It is plausible that modest attention to the chemical processing could bring the two parameters within specification.

2.5. Technology conclusions

Although further investigation is required, particularly with regard to material compatibility and thermal stability, it appears plausible that low concentration biodiesel in kerosene blends could be utilized in commercial aviation without impacting upon aircraft, flight operations, or airport infrastructure. This in no way contradicts previous studies exploring the prospects for alternative fuels [18,19], including the IPCC Special Report on Aviation and the Global Atmosphere [20],[8] as none of these reports considered the possibility of using low concentration biodiesel in kerosene blends.

The investigations of both the Purdue group and Dunn are ongoing, and further results are expected to appear in the literature in the near future.

3. Concerns over the use of fossil fuel

The current usage of kerosene as the fuel for commercial aviation raises a number of concerns, including:

3.1 National energy security: A number of countries, including the US and the EU countries (which, together, account for more than half of the world total jet fuel consumption[9,10]), are dependent on crude oil imports (Appendix C).
3.2 Ground level air pollution: In metropolitan areas, typically ~1% of ground level air pollutants, such as oxides of nitrogen, originate from aircraft exhaust emissions, and this percentage is forecast to rise over the coming decade [21].
3.3 Increasing atmospheric carbon dioxide: The combustion of fossil fuels increases the concentration of carbon dioxide in the atmosphere. There is concern that this may lead to a significant change in global climate [22].

[8] This report was produced at the request of the International Civil Aviation Organization (ICAO), and updated information can be found at their website (http://www.icao.org/cgi/goto_atb.pl?icao/en/env/overview.htm;env).

[9] Energy Information Administration, US Department of Energy.

[10] Table E4, International Energy Outlook 2002, Report number DOE/EIA-0484(2002) (see footnote 9) (http://www.eia.doe.gov/oiaf/ieo/tbl_e4.html).

3.4 Sustainability: The world reserve of crude oil is finite, and will, most likely, be exhausted early in the second half of this century (Appendix D).

The substitution of kerosene with biodiesel is not likely to have any impact on Concern 3.2 (see Section 2.4.5), but does directly address Concerns 3.1, 3.3 and 3.4 (both the US and EU currently have surpluses of vegetable oil production (Appendix E) and biodiesel can, in principle, be produced and consumed indefinitely, without causing any increase in atmospheric carbon dioxide (to be discussed in Section 6.1.2)).

Because of the concerns, some passengers might be prepared to pay an increased fare and fly on “green fuel” (in reality, biodiesel), in place of kerosene. To such a passenger, it should not matter if the biodiesel they purchase is used on their flight, or on a different flight, even a flight operated by a different airline, on a different route, at a different time. To illustrate this, consider carbon dioxide increase (Concern 3.3). The passenger’s purchase of biodiesel will help reduce carbon dioxide increase, the amount of reduction being the same, regardless of the flight on which the biodiesel is consumed.

4. Prototypical green air miles market

If it should prove technically feasible to use biodiesel/kerosene blends in commercial aviation (Section 2), even if only on a restricted subset of flights, then it would be possible to give all passengers, regardless of their route, the option of flying on “green” fuel. This is because those airlines operating aircraft on biodiesel/kerosene blends could create “green air miles”, in accordance with the number of passengers they carried on biodiesel, and then sell the green air miles to other airlines via an international green air miles market. This would be analogous to the trade of green energy certificates which already occurs between electricity companies in some deregulated electricity markets [23].

Suppose an airline, *A*, makes a flight from New York to Los Angeles, using B5Jet (see Section 2.4.1) as the fuel. As a consequence of the flight, the airline is allowed to create green air miles, according to the equation:

$$\begin{array}{l} \text{number of green air miles} \\ \text{(in units of green passenger} \\ \text{nautical miles)} \end{array} = \begin{array}{l} \text{number of passengers carried} \\ \times\ 2150 \text{ nautical miles} \\ \times\ 0.05 \times \Gamma \end{array} \tag{1}$$

where 2150 nautical miles is the distance by air between New York and Los Angeles,[11] 0.05 is the fraction of fuel by volume which is biodiesel, and Γ is a constant, with value ~0.66, which takes into account a number of technical details (Γ is discussed more fully in Section 6.1). Note that green air miles would be an electronic

[11] Obtained using the “Fare finder” “Advanced search” at United Airlines (http://www.ual.com).

commodity, similar to the money in most modern bank accounts. Airline *A* can sell the green air miles to the international green air miles market, as shown in Fig. 3. The market is simply a computer, located at one place in the world. The market allows airlines to participate in the electronic trading of green air miles.

Now consider a passenger who wishes to fly from Amsterdam to Madrid. The passenger is given the choice of making the journey on fossil fuel, making the journey on "green" fuel (in reality, biodiesel), or making just a fraction of the journey on green fuel, and the remainder on fossil fuel. The passenger decides the cost of making 100% of the journey on green fuel is beyond her budget, but she is prepared to pay the cost of making 10% of the journey on green fuel (the price premium to fly a fraction of a journey on green fuel will be derived in Section 6). She also wishes to fly with airline *B*. As it happens, airline *B* operates all its aircraft on 100% kerosene (it is envisaged that, notwithstanding limitations imposed by technology and fuel availability, airlines will have the freedom to choose the fuel on which they operate). Airline *B* can still *lawfully* sell the passenger the ticket she desires, *provided, at the time of sale*, it destroys green air miles *already in its possession*, totalling:

$$\text{number of green air miles to be destroyed} = 908 \text{ nautical miles} \times 0.1 \qquad (2)$$

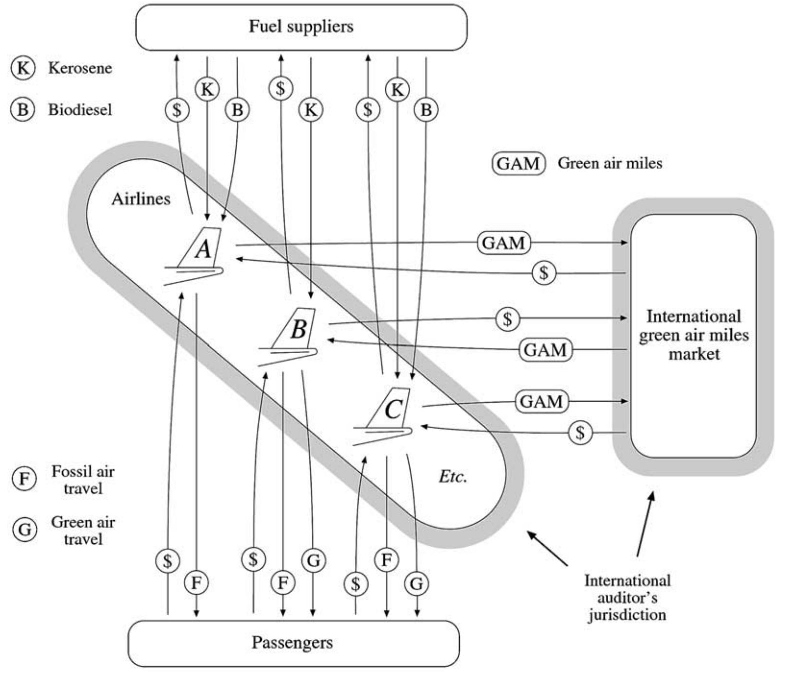

Fig. 3. How airlines would purchase fuel, sell air travel, and trade green air miles, if green air travel was introduced.

where 908 nautical miles is the distance by air between Amsterdam and Madrid,[12] and the 0.1 takes into account the fraction of the passenger's journey made on green fuel. Insisting that the airline has the green air miles in its possession prior to the ticket sale, should ensure a simple, stable market. In this case, the airline would purchase the green air miles from the market, as shown in Fig. 3. The passenger's ticket purchase forces the airline industry, collectively, to purchase sufficient biodiesel for 10% of her journey, although the biodiesel, in this case, is not used on her flight. If airline *B* purchases the green air miles from airline *A*, the biodiesel is used instead on a flight between New York and Los Angeles.

Note that those airlines using biodiesel blends, could sell the green air miles they were creating directly to their customers, as well as to the market, as shown in Fig. 3 for airline *C*.

Since biodiesel is more expensive than kerosene, an airline operating an aircraft on biodiesel will incur additional costs. Green air miles therefore have a cost of production, which will be quantified in Section 6.2. When selling green air miles on the market, airlines will try and recover this cost. Otherwise it is envisaged that the price of green air miles will be free from regulation and determined only be the intersection of supply and demand.

In order to eliminate the possibility of fraudulent transactions, such as the fraudulent creation of green air miles, it would be necessary to establish an independent auditor, whose jurisdiction is also indicated in Fig. 3. The function of the auditor would be to ensure the amount of biodiesel consumed by the aviation industry remains consistent with the amount of green travel the industry sells to passengers. If it is made mandatory that *all* airlines print on *all* passenger boarding passes, the distance of the flight, and the fractions of the journey being made on fossil and green fuels, the auditor's task simplifies to ensuring that the quantity of biodiesel consumed by the industry is consistent with the sum of green travel printed on all boarding passes. In this way, the scrutiny of passengers can be expected to perform a significant fraction of the auditor's task. The tagging of green air miles with information about the flight from which they were produced (airline, route, date, time), would assist the auditor trace transactions, should any anomolies become apparent. In this regard, it might also be prudent to restrict participation in the green air miles market to airlines, excluding the possibility of other parties purchasing green air miles and then on-selling them.

There would be a cost involved in first establishing both the green air miles market and the auditor's office, and also a cost involved in their ongoing maintenance. A precise estimate of the cost is beyond the scope of this report, but as a preliminary estimate, suppose each requires 50 skilled employees, each earning \$50 000 per annum, and that labour costs represent half of total costs (operating an airline is presumably more equipment intensive, and yet, even for airlines, labour costs are typically about 30% of total costs [24,25]). The total cost for the market and auditor's

[12] Obtained using "Fast flight finder & booking" at KLM Royal Dutch Airlines (http://en.spain.klm.com/).

office is then \$10 million per year. It would seem equitable to fund this by a levy on all airfares, regardless of fuel mix, as the market and auditor's office are part of a mechanism which enables passengers to choose the fuel mix on which they fly, including those passengers who choose to fly on 100% fossil fuel. In 2000, passenger revenues for the world's scheduled airlines totalled approximately \$237 billion (Appendix A). Funding the market and auditor's office by a levy on all airfares would therefore raise the average fare price by approximately 0.004%, a rise too small to be noticed by consumers.

5. The marketing of green air travel

The sale of an airline ticket involves the mutual exchange of information between vendor and purchaser. The vendor (an airline, for example) must inform the purchaser (prospective passenger) of the routes they fly, times of departure, availability of seating, and so on. Similarly, the prospective passenger must inform the vendor of the flight they have selected, whether they wish to fly business class or economy, their name, and so on. This mutual exchange of information provides an opportunity to effectively market travel on "green" fuel to essentially all prospective passengers, while incurring negligible cost.

To illustrate this, consider a passenger using the internet to purchase a ticket directly from an airline. A prototypical web page for part of the ticket sale is shown in Fig. 4. The prospective passenger wishes to fly economy class from London to Hong Kong, leaving on the afternoon of May 3, and has selected these on a previous page. The web page shown in Fig. 4, requests the passenger to enter the fuel mix they wish to fly on, offering them guidance by indicating the 100% fossil ticket price (in this case, UK£628.90) and the 100% green fuel price (in this case, UK£798.70), as well as providing a hyperlink to further information about the green fuel scheme. Once the passenger has entered a fuel mix, the web page advises them of the consequent ticket price and gives them the option of either revising their fuel mix or continuing to the next stage of ticket purchase.

Note how, by specifying no default fuel mix, the web page effectively markets travel on green fuel to the prospective passenger—the passenger cannot complete ticket purchase until they have recognized that they have a choice of fuel mix and have considered this choice. Furthermore, the marketing strategy (of requiring the passenger to choose their fuel mix, and specifying no default) is not restricted to online purchasing. Consider, as a further example, a prospective passenger purchasing a ticket via a face-to-face meeting with a travel agent. The travel agent will both give the passenger information (which airlines fly which routes, etc.) and collect information from them (the airline the passenger would like to fly with, etc.), guided largely by the global distribution system (GDS) [26] that the travel agent is using. If the GDS requests information about fuel mix, the travel agent will seek to get this information from the prospective passenger, either verbally, or perhaps by encouraging the passenger to follow a screen on their computer, provided by the GDS, similar to Fig. 4.

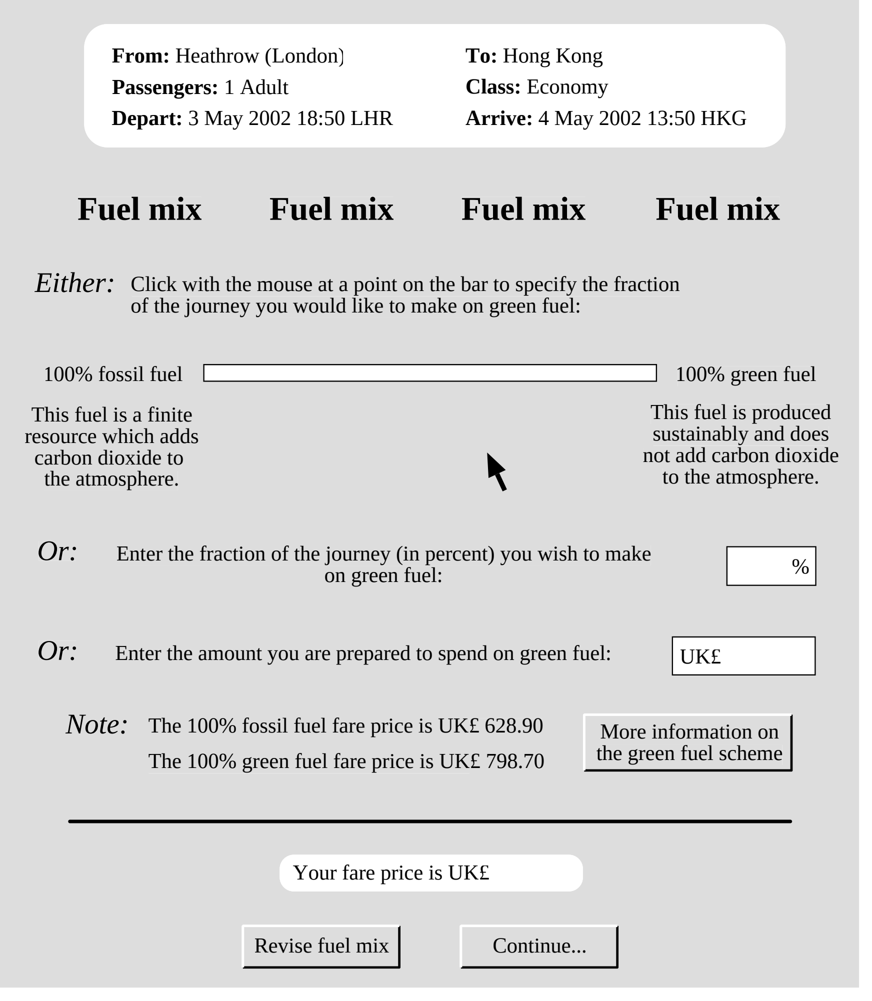

Fig. 4. Prototypical web page for one step in the purchase of an airline ticket. Note that this is not the first step—the prospective passenger has already specified some information, such as route, on a previous page.

The cost of implementing the marketing strategy is the cost of modifying booking systems (airline web sites, GDSs, etc.) so that information regarding fuel mix is collected from passengers and then relayed back to airlines. Since choice of fuel mix is a service provided to all passengers, regardless of which fuel they actually choose, it would seem equitable to pass on the cost of implementation to all passengers in the form of a short term rise in airfares. As in the case of the green air miles market and the auditor's office (see Section 4), this rise in airfares is anticipated to be so small as to be undetectable by passengers. Once implemented, the marketing strategy would incur no ongoing costs.

As mentioned in the introduction, airlines might wish to encourage passengers to fly on green fuel as a means of securing the airline industry from concerns surrounding fossil fuel usage. If they wished, airlines could include specification of fuel mix as a mandatory step in their own ticket sales. However, airlines are not the only vendors of air tickets. Mention has already been made of the GDS/travel agent combination. It would seem likely that at least one GDS would adopt the marketing strategy of mandatory specification of fuel mix, either because it represents a service edge over competitors, and/or because the GDSs have almost as great an interest in securing the future of the airline industry as the airlines themselves. Once one GDS had adopted mandatory specification of fuel mix, airlines could exert great pressure on any GDS which did not follow suit (for example, threatening not to renew contracts for further ticket sales).

There are also additional vendors selling air tickets via the internet. These operate using a number of different trading models, and, in recent years, have represented part of the industry in rapid evolution [27]. Of all the trading models, the one least suited to specification of fuel mix is probably the reverse auction trading model, as exemplified by priceline.com.[13] In this model, the prospective passenger first specifies where and when they wish to fly, and the price they are prepared to pay. The vendor then tries to find an airline prepared to offer a ticket at that price. However, even in this model, the specification of fuel mix could still be included as a mandatory requirement (prospective passengers would have to specify where and when they wish to fly, the fraction of the journey they wish to make on green fuel, and the price they are prepared to pay). The one difficulty is that, at least initially, consumers would not have a good appreciation of how ticket prices grow with the fraction of journey made on green fuel.

It would seem that, should they desire it, the airlines could also force all the internet vendors to adopt mandatory specification of fuel mix (they could, for example, pressure GDSs to suspend trade with any internet vendor that failed to adopt this marketing strategy). It therefore seems that there is not only a low cost, effective marketing strategy for green air travel, but that the marketing strategy could easily be expanded to reach essentially all prospective passengers.

6. Price premium for green air travel

This section derives the additional price passengers will need to pay to fly on “green” fuel. The first step in the derivation (Section 6.1) is to complete the definition of eq. (1) (see Section 4), which relates the number of green air miles an airline may create to the flights the airline has made on biodiesel. The second step in the derivation (Section 6.2) is to determine the additional operating cost use of biodiesel imposes on an airline. Ultimately, the additional cost will be passed on to consumers

[13] http://www.priceline.com

purchasing green air travel, and it is this that allows the price premium for green air travel to be determined (Section 6.3).

6.1. The rule for creating green air miles

If Γ was omitted from eq. (1) (see Section 4), green air miles would be generated in proportion to distance flown, number of passengers carried, and fraction of fuel by volume which is biodiesel. The presence of Γ allows the inclusion of a number of small, but important, technical corrections.

6.1.1. Fraction of fuel by energy

When an aircraft is fuelled using a biodiesel/kerosene blend, the fraction of the journey made on biodiesel should be proportional to the fraction of the energy of the fuel which has come from biodiesel, rather than the fraction of the volume of the fuel which has come from biodiesel. Γ should therefore contain the factor:

$$\text{energy per unit volume (biodiesel)} \div \text{energy per unit volume (blend)}$$

Using data from Table 1, this is 0.938 for B5Jet.

6.1.2. Green fuel standard

The web page in Fig. 4, requires passengers to specify the amount of “green” fuel, rather than “biodiesel”, that they wish to fly on (although biodiesel might be discussed under the hyperlink “More information on the green fuel scheme”). Avoiding specific reference to biodiesel is important for two reasons. Firstly, it explains to passengers the choice they are making, without introducing unnecessary detail. Secondly, it leaves open the possibility of introducing other alternative fuels, such as other biofuels or liquid hydrogen [18–20],[14] which airlines might use in their aircraft to generate green air miles.

The web page also makes the claim that, the “fuel is produced sustainably and does not add carbon dioxide to the atmosphere”. Again the wording is carefully chosen to be accurate, clear and concise. An alternative fuel used to generate green air miles should approximately satisfy this claim (“green fuel standard”). This is important, not only to underpin the integrity of the scheme for consumers, but also to provide a level playing field on which rival alternative fuel technologies can compete.

The production of biodiesel requires energy, for example, transportation fuel for agricultural machinery, such as tractors, and electricity for the factory which converts oil or fat into biodiesel. In principle, a fraction of each year’s biodiesel output could be set aside to provide the energy to produce the following year’s biodiesel. However, in practice this is not done, and typically ~0.3 MJ of fossil fuel is used to

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[14] For current research on liquid hydrogen in aviation see the European Cryoplane project (http://www.eads.net/eads/en/index.htm?/xml/en/businet/airbus/cryoplane/cryoplane.xml&airbus) and the NASA Zero CO_2 research project (http://www.grc.nasa.gov/WWW/AERO/base/zero.htm).

produce each MJ of biodiesel [28]. In order to comply with the green fuel standard, only 0.7 MJ of each MJ of biodiesel loaded onto a plane should therefore be considered available for green air travel, the remaining 0.3 MJ being required to offset a quantity of fossil fuel which has already been used in biodiesel production. Γ should therefore include a factor of 0.7 MJ/1 MJ = 0.7.

It should be emphasized that the value of 0.3 MJ is only an approximation. The exact value will differ from one biodiesel producer to another, for example, some producers may use electricity derived from fossil fuels, while others use electricity derived from hydro-power. Also, identifying the fossil fuels used to produce the biodiesel is intrinsically difficult. For example, fossil fuels may be used to *manufacture* a tractor used in the production of biodiesel. Should these fossil fuels be included? One final difficulty is that the 0.3 MJ of biodiesel loaded onto the plane which is assigned to offset 0.3 MJ of fossil fuels in the biodiesel production process, actually offsets 0.3 MJ of kerosene, while coal or natural gas are much more likely to have been used in producing the biodiesel. This is a difficulty because, for a given amount of energy, each of the fossil fuels adds a somewhat different amount of carbon dioxide to the atmosphere when combusted, natural gas producing the least, coal the most (about a factor of two more than natural gas), and kerosene being somewhere between the two extremes (see page 349 of [29]).

Although the value of 0.3 MJ is only an approximation, this is unlikely to be problematic. If industry or consumer groups felt the value was either too low or too high for biodiesel to conform with the green fuel standard, the value could be revised, either upward or downward. Any such revisions are envisaged to be small and will not be considered further.

6.1.3. Freight

If on a flight using biodiesel, the aircraft is carrying both passengers and freight, the number of green air miles produced should also be weighted by $(m_p + m_f)/m_p$, where m_p is the mass of the passengers (including their baggage) and m_f is the mass of the freight. For the flight operations in Section 6.2, the aircraft carry no freight, and it will not be necessary to consider freight further in this paper.

Combining the results of Sections 6.1.1 and 6.1.2, the value of Γ for B5Jet should be $0.938 \times 0.7 = 0.66$.

6.2. Cost of production of green air miles

From the perspective of an airline, the operation of an aircraft on a biodiesel/kerosene blend incurs additional cost in comparison to operation on pure kerosene. If aircraft can be operated on blend without modification, and without the need for additional maintenance (see Section 2), then the additional cost is restricted to the additional cost of the fuel. The operation of an aircraft on blend also allows airlines to generate additional revenue from the production and sale of green air miles. Airlines will only elect to operate on blend if the revenue they can raise from the sale of green air miles at least equals the additional fuel cost of operating on

blend. Hence, there is a minimum price at which airlines can be expected to offer green air miles, either directly to their customers in the form of green air travel, or to the green air miles market. This price can be determined from fuel cost calculations.

6.2.1. Price of kerosene

Fig. 5 indicates the prices airlines have paid for kerosene in recent years.[15] Comparison of the two data sets on the figure shows the price of fuel does have some geographic dependence (US verses rest of world). However, the difference is small. Note also that, to good approximation, fuel for international flight operations is exempt from taxation (see Chapter 10, [20]). From the graph, a reasonable estimate for the price airlines will pay for kerosene in the immediate future is approximately 70 cents per gallon. However, the uncertainty is large (+/−20%).

6.2.2. Price of biodiesel

The price of biodiesel depends on the feedstock used. Possible feedstocks include vegetable oils, such as soy and rapeseed, recycled cooking oils and greases ("yellow grease"), and tallow (animal fat) [4]. Recycled oils and greases, and tallow, are currently less expensive feedstocks than vegetable oils, at least in part because they are low cost by-products of other industries (the restaurant industry and meat industry respectively). However, there are reasons why vegetable oils may be preferred for the generation of green air miles. For example, biodiesel made from yellow grease

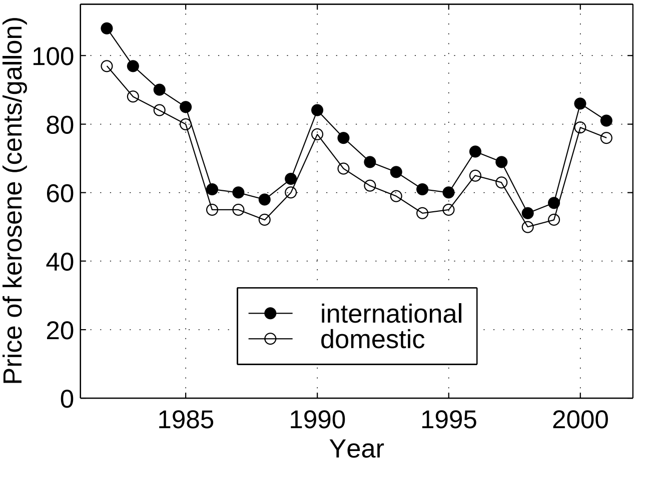

Fig. 5. Trends in the price of kerosene purchased by US airlines. The domestic price is the total annual expenditure by US airlines (major, national and large regional carriers) on fuel for domestic flights, divided by the total fuel consumed during those flights. Similarly, the international price is the total annual expenditure by the same airlines on fuel for flights, either departing from and/or arriving at, destinations outside the US, divided by the total fuel consumed during those flights.

[15] Data from: Office of Airline Information, (see footnote 3) (http://www.bts.gov/oai/fuel/fuelyearly.html).

is known to have poorer cold flow properties (Section 2.4.2) than biodiesel made from soy [30]. The use of tallow, an animal product, may alienate some vegetarians. In making this last remark, it is perhaps worth pointing out that green air travel will, in all probability, only be purchased by a small subset of prospective passengers (to be estimated in Section 7). People in the subset share a high level of concern about the environment/sustainability, and may share a high level of concern about related issues, such as animal welfare. It is therefore plausible that the subset might contain a much greater fraction of vegetarians than is found in the population at large.

Of the vegetable oils, European biodiesel production has mainly used rapeseed, while US biodiesel production has mainly used soy [4]. US production of soybeans currently accounts for one quarter of global oilseed production.[16] Fig. 6 shows the price US farmers have received for soybeans in recent years. During the interval 1982–1996, the US Government provided growers with financial support when prices were low and reclaimed the money from growers when prices were high. The overall transfer of funds was approximately zero (see footnote 16). Genetically modified (GM) soy was first introduced for commercial plantation in 1996.[17] Hence the data from 1982–1996 gives a reasonable indication of the price of soybeans in the absence of government intervention or genetic modification. Note that non-GM soy is chosen in preference to GM soy as the use of genetically modified organisms may alienate a significant fraction of the potential market, as outlined above for tallow. Note also that, in 2000, US growers received financial support from the US Government equal

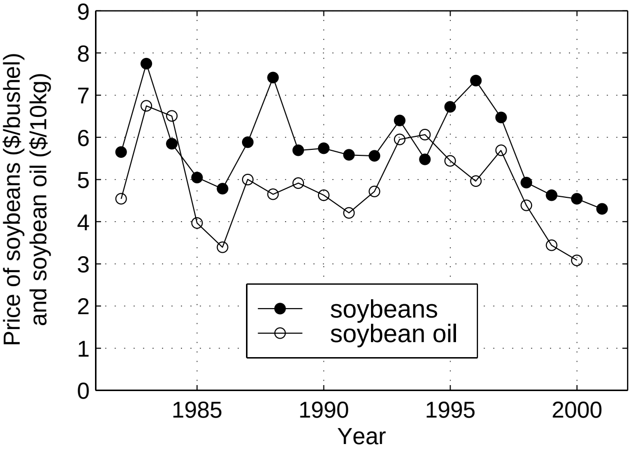

Fig. 6. Trends in the price of soybeans and soybean oil for the US. For soybeans, each point on the graph is an annual average (total annual soybean sales divided by total annual production[18]). The data for soybean oil has come from footnote 16, and is assumed to be calculated similarly.

[16] Soy Stats 2001, American Soybean Association, Missouri (http://www.soystats.com/).

[17] American Soybean Association (http://www.soygrowers.com/?p=384).

[18] Data from: National Agricultural Statistics Service, US Department of Agriculture (http://www.nass.usda.gov:81/ipedb/).

in value to approximately 20% of their income from soybean sales (see footnote 16). The purpose of the financial support was to compensate growers for the low price of soy. The extent to which the availability of financial support precipitated the low price is debated.

Also shown in Fig. 6 is the annual average price of soybean oil. Using the data from 1982–1996, a reasonable estimate for the price of non-GM soybean oil, in the absence of government intervention, is approximately 5$/10 kg with an uncertainty of approximately +/−20%.

It takes 7.3 lb (3.3 kg) of soybean oil to produce 1 gallon of biodiesel.[19] The purchase price of biodiesel from the production plant is given by the feedstock cost plus 21 cents per gallon of biodiesel [30]. Neglecting the cost of transporting biodiesel from production plant to airport, the price airlines can expect to pay for biodiesel suitable for the generation of green air miles is therefore approximately 1.86$/gallon. Note that, if green air travel grew to 1% of all air travel sold, this would have a significant impact on world oilseed consumption (Appendix E), potentially raising this price.[20] Any such price rise is neglected in the remainder of this paper.

6.2.3. Aircraft fuel consumption

Fuel cost calculations have been performed for three different aircraft. The Saab 340B seats approximately 30 passengers, is powered by two turboprops, and is designed to feed major airline hubs and serve regional routes.[21] The Boeing 717-200, a derivative of the Douglas DC-9,[22] seats approximately 100, is powered by two turbofans, and is designed to service short haul, high frequency routes.[23] The 747-400 seats approximately 400 passengers, is powered by four turbofans, and is designed to service long haul routes.[24] Note that, especially in the case of the Boeings, there can be considerable variation among aircraft of the same model (seatings for different numbers of passengers, for example). Hence the calculations were performed for specific aircraft. Technical specifications were available for these aircraft, either because they were available for lease, or because they were being sold.[25–27] A summary of relevant technical specifications is given in Table 2, and approximate payload-range curves are shown in Fig. 7.

Calculations were performed for four flights, two with the Saab, and one with each of the Boeings. The payloads to be carried and distances to be flown are listed

[19] Alternative Fuels Data Center, US Department of Energy (http://www.afdc.doe.gov/altfuel/bio_general.html#market)

[20] Biodiesel's potential impact to farmers, National Biodiesel Board, September 1999 (http://www.biodiesel.org/resources/reportsdatabase/reports/gen/gen-194.pdf).

[21] http://www.saabaircraft.com/GeneralWebServices/GeneralInformation.asp?fromMenu=true&serviceid=1&nodeid=47&Pageid=30

[22] http://www.flug-revue.rotor.com/FRtypen/FRMD-95.htm

[23] http://www.boeing.com/commercial/717/background.html

[24] http://www.boeing.com/commercial/747family/background.html

[25] http://www.saabaircraftleasing.com/products/340b/340B.pdf

[26] http://www.boeing.com/commercial/airtrade/minispec/55088.pdf

[27] http://www.boeing.com/commercial/airtrade/minispec/25879.pdf

Table 2
Specifications for three aircraft and data for flight operations. Note that nm means nautical miles

Aircraft	Saab 340B		Boeing 717-200	Boeing 747-400
Specifications:				
Year of manufacture	After 1987[a]		2000	1992
Engines	Two turbo-props		Two turbo-fans	Four turbo- fans
Passenger seating	34 (single class)		100 (two classes)	404 (three classes)
Operating empty weight, lb	19,000		68,820	404,339
Maximum zero fuel weight, lb	26,500		100,500	535,000
Fuel capacity, lb (gallons)	5,690 (845)		24,730 (3,673)	363,500 (53,985)
Maximum takeoff weight, lb	29,000		118,000	850,000
Maximum operating altitude, feet	25,000		37,000[b]	45,000[c]
Flight operations:				
Label	*A*	*B*	*A*	*A*
Distance, nm	0.8×1,255=1,004	0.8×423=338	0.8×1,630=1,304	0.8×6,692=5,354
Payload, lb (passengers @ 210 lb each)	4,200 (20)	7,140 (34)	21,000 (100)	84,840 (404)
Kerosene required, lb (gallons)	0.8×5,690=4,552 (676)	0.8×2,860=2,288 (340)	0.8×24,730=19,784 (2,938)	0.8×363,500=290,800 (43,188)
Value of kerosene, $	473	237.9	2,057	30,228

(*continued on next page*)

Table 2 (*continued*)

Aircraft	Saab 340B		Boeing 717-200	Boeing 747-400
Fuel efficiency, passenger nm per gallon	29.7	33.8	44.4	50.1
B5Jet required, lb (gallons)	4,587 (678)	2,306 (341)	19,937 (2,948)	293,030 (43,325)
Value of B5Jet, $	514	258.4	2,234	32,840
Fuel cost excess, $ (based on overestimate, $)	40.9 (41.4)	20.5 (21.2)	177.7 (183.5)	2,612 (2,773)
Green passenger nautical miles produced	663	379	4,303	71,370
Cost of production, cents per green passenger nm	6.2	5.4	4.1	3.7

[a] http://w1.873.telia.com/-u88203139/k100e/bilar/carmakes/k1casaa2.htm
[b] See footnote 22.
[c] http://www.e-flight.com/747-400.htm

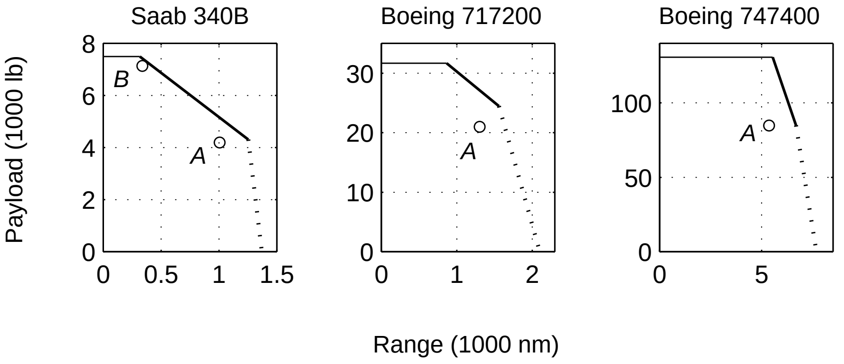

Fig. 7. Payload-range curves for three different aircraft. In the case of the Saab, the curve represents a compromise between the aircraft being flown at maximum cruise and long range cruise. Note that, the thin part of each curve corresponds to maximum payload, the thick part to maximum takeoff weight, and the dotted part to a full fuel load.

in Table 2, and the corresponding points plotted on the payload-range curves. Note that the three flights labelled *A* occupy qualitatively similar points on the payload-range curves, while flight *B* is somewhat different.

For each of the flights, the distance was chosen to be 80% of the maximum distance the aircraft could fly with the given payload. The amount of kerosene required to fly the 80% distance was assumed to be 80% of the amount of kerosene required to fly the maximum distance. This is not exactly correct, but is a reasonable approximation, as evidenced by sector performance data for the Saab (see footnote 25). The amount of kerosene, its cost, and the fuel efficiency (passengers carried multiplied by distance flown divided by fuel used) are also listed in Table 2.

As a first approximation, it was assumed that the flights could also be accomplished using B5Jet in place of kerosene, provided the energy content of the B5Jet equalled the energy content of the kerosene displaced. The amount of B5Jet required, its cost, and the difference between this cost and the kerosene cost (fuel cost excess) are all shown in Table 2 (see also Section 2.4.1).

As can be seen from the table, the mass of B5Jet exceeds the mass of kerosene displaced. This will reduce the distance the aircraft can fly to below that specified. An overestimate for the reduction in distance for flights of type *A* is given by:

$$\text{distance reduction} = \frac{\text{mass of B5Jet} - \text{mass of kerosene}}{|\text{gradient of dotted part of payload-range curve}|} \tag{3}$$

Assuming the distance flown is linearly related to the amount of B5Jet, an overestimate for the amount of B5Jet required to fly the specified distance is then given by:

$$\text{overestimate amount of B5Jet} \tag{4}$$

$$= \frac{\text{amount of B5Jet from first approximation} \times \text{distance to be flown}}{\text{distance to be flown} - \text{distance reduction}}$$

Using eqs. (3) and (4), overestimates for the amount of B5Jet were calculated. The corresponding fuel cost excesses are shown bracketed in Table 2. In the case of flight *B*, an overestimate for the amount of B5Jet can be obtained in a similar fashion using the gradient of the thick part of the payloadrange curve. The calculation is slightly more complicated, requiring also use of the sector performance data (see footnote 25), and will not be described here, but the result for the fuel cost excess is shown bracketed on the table. Comparison of the bracketed and unbracketed fuel cost excess values, indicates that the difference in mass between amounts of B5Jet and kerosene of equal energy is not a significant factor in the production cost of green air miles.

Finally, Table 2 shows the number of green air miles produced by each flight (recall from Section 6.1 that, for B5Jet, $\Gamma = 0.66$) and their cost of production. The cost of production was also evaluated for other concentrations of biodiesel in kerosene, spanning the range 0–10% biodiesel in kerosene (by volume). The variation in cost of production with blend concentration was found to be negligible (less than 1%).

As can be seen from Table 2, the production cost of green air miles is different for different aircraft. Large, long haul aircraft can produce green air miles at less cost, a reflection of their superior fuel economy. It is plausible that green air miles might trade on the green air miles market for ~4.2 cents per green passenger nm. At this price, the operators of smaller, turboprop aircraft would continue to use 100% kerosene (recall from Section 4 that, notwithstanding technical limitations, it is envisaged that airlines would remain free to operate on the fuel of their choice).

6.3. Green air fares

A useful measure of the price passengers pay to fly with an airline is provided by the *yield* of the airline. The yield is defined here as the passenger revenue per passenger mile, that is, the total revenue the airline receives from passengers during the course of a year divided by the total distance flown by all passengers with the airline during the same year. To give two examples, for the year ended December 31, 2000, United Airlines[28] had a yield of 13.25 cents per passenger statute mile [24],[29] while, for the year ended 31 March 2001, SkyWest Airlines[30] had a yield of 40.0 cents per passenger statute mile [25].[31] These airlines have been chosen as an

[28] http://www.ual.com/

[29] That the figures quoted in reference [24] are statute miles, can be deduced by comparing the figures in reference [24] with the figures for United published by the Air Transport Association (ATA) (see footnote 36). That the figures published by ATA are for statute miles can be deduced by comparing their values for total revenue passenger miles with those from the Office of Airline Information (see footnote 1) (http://www.bts.gov/oai/indicators/top.html—see, in particular, the glossary of terms).

[30] http://www.skywest.com/

[31] The figures quoted in reference [25] are also statute miles (private communication from G. Carter, Executive Assistant - Finance, SkyWest Airlines, Inc.—Gcarter@skywest.com).

example of an international carrier, operating large and/or long haul aircraft, and a regional carrier with a predominantly twin turboprop fleet respectively.[32]

Since airlines use the revenue they receive from passengers to cover the cost of carrying passengers, the yield is also approximately equal to the cost an airline incurs in carrying passengers. In other words, to carry one passenger, one statute mile, costs United approximately 13.25 cents in wages, fuel, aircraft maintenance, and so on. That the yield for SkyWest is greater, reflects the greater cost involved in carrying smaller numbers of passengers over shorter distances.

The yields quoted for the two airlines are relevant for the case of fossil fuelled air travel. If the airlines wish to offer air travel on green fuel, they will face the additional cost of either operating one of their own aircraft on biodiesel/kerosene blend, or of purchasing green air miles from the market. As shown in Section 6.2, this cost is approximately 4.2 cents per green passenger nautical mile (3.6 cents per green passenger statute mile). Airlines will recover this additional cost by making green fares more expensive than fossil fares. To fly with United, making 100% of the journey on green fuel, will cost ~ 13.25 + 3.6 cents per passenger statute mile (27% more than the 100% fossil fuel fare). Similarly, to fly with SkyWest, making 100% of the journey on green fuel, will cost ~ 40.0 + 3.6 cents per passenger statute mile (9% more than the 100% fossil fuel fare).

7. Demand for green air travel

In Section 6.3, it was shown that the price premium for flight on 100% “green” fuel would be ~9% for travel with a regional airline, and ~27% for travel with a national or international airline. The purpose of the present section, is to estimate the fraction of the market, flight on green fuel would capture, given these price premiums, and assuming that flight on green fuel is marketed as being environmentally and socially benign. Since green air travel has never been sold before, the only means of estimation is to compare with similar products already being sold. For green air travel, the only similar product would appear to be green electricity.

The airline and electricity industries are actually quite similar. Table 3 shows US expenditure on air tickets and electricity. Note that the figures are quite similar, both for the total expenditure and the division of expenditure between households and businesses. Also, the generation of electricity using fossil fuels raises concerns similar to those in Section 3, the ground level pollution in Concern 3.2 being associated with power stations rather than airports.

Green electricity (also called green power) [23,31] is electricity generated using technologies, such as wind power, which address Concerns 3.1–3.4, in much the same way as the use of biodiesel in commercial aviation would address Concerns

[32] The size of United, in comparison to the other US international carriers, is given in footnote 36. Similarly, the size of SkyWest in comparison to other US regional airlines is given by the Regional Airline Association (http://www.raa.org/carriers/TopAirlines.xls).

Table 3
Expenditure on air tickets and electricity in the US for the year 2000

	Total expenditure by all consumers (households and businesses) (billion $)	Percentage of total expenditure which is due to households
Air tickets	97[a]	31%[b]
Electricity	224[c]	43%[c]

[a] This is the total passenger revenue for all US airlines obtained from: Air Carrier Financial Statistics 2000 (the "Yellow Book"), Office of Airline Information (see footnote 1) (http://www.bts.gov/oai/aviation_industry/YellowBook_Dec2000.pdf). This number will differ from the total value of air tickets purchased by US consumers because US airlines sell some tickets to non-US customers. However, US customers can also purchase tickets from non-US airlines, so the difference between the two numbers is not expected to be large.
[b] In the year 2000, US households spent $30 billion on air tickets. From all Consumer Unit pre-publication table for the years 1994–2000, Consumer Expenditure Survey, Bureau of Labor Statistics, US Department of Labor (http://www.bls.gov/cex/home.htm).
[c] Executive Summary, Electric Sales and Revenue 2000, see footnote 9 (http://www.eia.doe.gov/cneaf/electricity/esr/esr_sum.html).

3.1, 3.3 and 3.4 (however, the use of biodiesel also raises a concern, which the green electricity technologies do not—this will be discussed more fully in Section 8). Green electricity and green air travel are also similar in that, in both cases, the concerns in Section 3 provide the only motive for consumers to purchase the green product in preference to its ordinary counterpart (consumers of green electricity cannot distinguish the electricity they receive from ordinary electricity, in much the same way as passengers would experience the same ride, regardless of the fuel on which they were flown (Conclusion 1.4, Section 1)). One final similarity is that, when a consumer purchases green electricity, the electricity industry is obliged only to generate the electricity using green technology, not to deliver it specifically to the consumer. The purchase of flight on green fuel would be similar, with the airline industry obliged to use a quantity of green fuel, but not necessarily on the purchasing passenger's flight (see Section 4).

Since the 1990s, sales of green electricity have been introduced by a number of electricity vendors across the globe.[33] Each vendor sells green electricity at some *price premium* (difference in price between green electricity and ordinary electricity as a percentage of the price of ordinary electricity). Also, for each vendor, green electricity sales are some percentage of total electricity sales (which will be defined here as the *market share* for green electricity). If the relationship between price premium and market share for green electricity is known, and the price premium

[33] The status of green electricity sales in the US is reviewed in [31]. Updated information is available from the Energy Efficiency and Renewable Energy Network of the US Department of Energy, http://www.eren.doe.gov/greenpower/summary.shtml. Information for other countries is available at http://www.eren.doe.gov/greenpower/international.shtml.

for green air travel is known, then the expected market share for green air travel can be inferred, as the two products are similar.

As part of the present study, price premium and market share data was collected for a subset of the US electricity vendors which sell green electricity. The vendors cannot be regarded as a perfect model for the sale of green air travel. For example, Concerns 3.1 and 3.4, relevant for green air travel, were not particularly relevant in the case of the vendors. Nevertheless, it is felt that the data collected from the vendors can act as a reasonable guide for what might be expected for green air travel. A full account of the collection is given in Appendix F. The results are shown in Fig. 8. The electricity vendors concerned are the Dakota Electric Association (Minnesota), Public Service Company of Colorado (Colorado), Dairyland Power Cooperative (Wisconsin), Lincoln Electric System (Nebraska), and Arizona Public Service (Arizona). For convenience, these are referred to by the names of the states in which they operate. In the case of Minnesota, Nebraska and Arizona, the data obtained was sufficiently detailed for the change of market share with time to be inferred (see also Fig. 11). In the case of Minnesota and Arizona, the market shares were still increasing; hence the upward arrows in Fig. 8. In the case of Nebraska, the market share was declining (although only slowly), and hence the reason for the downward arrow. For Colorado and Minnesota, the data obtained was not sufficiently detailed to indicate if the market share was rising, declining, or static. However, Wisconsin had thus far only offered green electricity to residential consumers, and, as data for Minnesota clearly shows, sales to business consumers can be significant. Hence, Wisconsin has also been given an upward arrow. For all five vendors, market share grew rapidly immediately after the introduction of green electricity sales, requiring only a month or two to exceed 50% of the values shown in Fig. 8.

Also shown in Fig. 8 is the range of price premiums for flight on 100% green

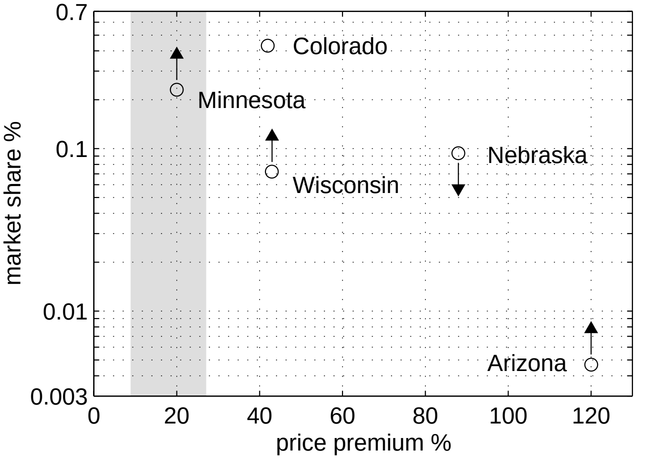

Fig. 8. Market share verses price premium for sales of green electricity by selected US utilities. The range of price premiums expected for green air travel is indicated by the shaded bar. Note the logarithmic scale on the vertical axis.

fuel. The high end of the range (~27%) corresponds to flight on 100% green fuel with a national or international airline. Note that flights with national and international airlines are of greatest interest, as they account for the vast majority of air travel. In the US, for example, regional airlines account for ~13% of tickets sold and ~4% of revenue passenger miles.[34] From the graph, the market share for green electricity, assuming a price premium of ~27%, is expected to be at least 0.1%. Furthermore, as commodities, electricity and air travel differ in two ways, both of which suggest that, assuming the same price premium, green air travel will achieve a greater market share than green electricity.

The first difference is that green electricity faces marketing obstacles that green air travel does not. It is impractical to bring the option of purchasing green electricity to the attention of a consumer every time the consumer uses electricity. It is even difficult to bring green electricity to the attention of the consumer at each bill payment, as there is no guarantee the consumer will read any advertising material delivered with their invoice. Even if the consumer does become aware they have the option to purchase green electricity, choosing this option requires some effort on their part. It is easier for them to do nothing, in which case they will continue to be supplied with ordinary electricity. The situation with air travel is different. As explained in Section 5, consumers could be made aware of green air travel at each ticket purchase. Furthermore, the selection of green air travel in preference to ordinary air travel would require no additional effort on the part of the consumer.

The second difference is that, for most consumers, electricity is an essential item which is difficult to substitute, while air travel is more of a luxury with greater scope for substitution. A typical consumer requires a fixed quantity of electricity (a certain number of kWh per month). If the consumer elects to purchase green electricity, it will increase their total expenditure, and this may be beyond their financial resources. In the case of green air travel, the same barrier is not quite so rigid, at least for many household consumers. Consider a tourist, planning a holiday in Greece. The cost of the fossil fuel ticket for the journey is $1000 and the tourist has budgeted for this. If the tourist wishes to fly on green fuel, they still have two holiday options which will allow them to do this. One is to retain the $1000 budget but choose a destination which is closer to home. The other is to defer the holiday until the extra ~$270, required to fly to Greece on green fuel, has been saved. Note that this example might suggest that the introduction of green air travel will reduce total air travel. This is not necessarily the case as, without the option of flying on green fuel, the environmentally conscious tourist might not fly at all.

To conclude this section, if the sale of green air travel was introduced, it seems certain that, within only a few months of its introduction, it would achieve a market share of at least 0.1%. Although more speculative, a market share as large as 1% is

[34] According to the Regional Airline Association (see http://www.raa.org/whoweare/factsheet.pdf), in the year 2000, passenger enplanements and revenue passenger miles for US regional airlines were 84.6 million and 25.25 billion, respectively. In the same year, according to the Air Transport Association (http://www.airlines.org/public/industry/bin/2001factfig.pdf), the passenger enplanements and revenue passenger miles for US scheduled airlines were 665.5 million and 692.505 billion, respectively.

not implausible. Note that, in this context, market share refers to the percentage of all air travel (total passenger-miles) sold.

8. Concerns over the usage of biodiesel

Although the substitution of kerosene with biodiesel in commercial aviation would address Concerns 3.1, 3.3 and 3.4 (see Section 3), it would also raise a new concern:

8.1 Land use: The production of biodiesel for aviation use would require agricultural land, land that might otherwise be used for food production, or used to produce biodiesel for essential transportation (such as the transportation of food), or preserved in its natural state.

From a "green" perspective, the substitution of kerosene with biodiesel therefore addresses concerns (Concerns 3.1, 3.3 and 3.4, particularly 3.3 and 3.4), and raises one concern (Concern 8.1). If Concern 8.1 was of a minor nature, flight on biodiesel could be introduced and marketed as "green" air travel. This would seem to be in everyone's interest. To those unsympathetic to the green agenda, it would have no impact, while, from a green perspective, it would:

- Empower environmentally conscious consumers all over the world to fly without compromising their values.
- Result in the substitution of non-sustainable technology with a sustainable alternative.
- Bring the sustainable technology into the market place, where the innovation associated with free enterprise could be expected to improve it further, lower its cost, and so on.

Determining the significance of Concern 8.1 therefore becomes of primary interest, and is the subject of this section. Note that, for green electricity, there is no analogous concern because, although the construction of wind turbines (for example) does require resources (such as land and engineers), it is difficult to envisage that the resources could be more usefully deployed for any other purpose.

The greatest ramification of Concern 8.1 is that the use of land to grow aviation fuel might jeopardize adequate food production. If green air travel grew to account for 1% of all air travel sold (Section 7), the global airline industry would require ~543 million gallons of biodiesel per year (see Appendices A and E). Using Table 1, this is 67 million GJ of biodiesel per year. Note that this is slightly greater than estimated world biodiesel production for the year 2002 [32]. Assuming biodiesel production from rapeseed in Germany [6], producing the biodiesel would require 1.4 million hectares of agricultural land. Currently, 1.4 million hectares of German agricultural land feeds ~7 million people (in the year 2000, Germany had a population of 82 million, an agricultural area of 17 million hectares, and a food balance

sheet suggesting it was approximately self-sufficient in food[35]). Producing the biodiesel using soy in the US would require an even greater land area (see footnotes 16 and 20).

The sale of green air travel would be unlikely to result in hunger in the developed nations. This is partly because these nations all have some sort of social security system to redistribute wealth, if necessary, to their poorest nationals, and partly because these nations all have sufficient export earning potential to import food if necessary. This is further illustrated as follows. Suppose the global resource of agricultural land was divided between food production and fuel production for aviation, and a food shortage loomed among the developed nations. As food became scarce, its price would rise. As food prices rose, the social security system in each country would transfer financial resources from the population at large to the poorest people, so that the poorest could still afford to eat. This would reduce the demand from the population at large for green air travel, while maintaining upward pressure on food prices. So some farmers growing aviation fuel would switch to growing food (as demand for aviation fuel would be dropping and food prices would be rising). The social security systems would continue to indirectly drive this change in land use, from fuel production to food production, until, either the food shortage was resolved, or until there was no land left in fuel production.

If all the world's nations were developed, there would therefore be no objection to the introduction of flight on biodiesel and its marketing as "green" air travel. However, at the present time, there are a number of nations which either do not have the export potential to import food (if necessary) and/or which do not have any form of social security. It is therefore necessary to quantify how sales of green air travel might divert agricultural resources away from food production and exacerbate undernutrition in these nations.

Appendix G gives an analysis of how the world's agricultural and fossil fuel resources would need to be allocated in order to eliminate the sufferings associated with undernutrition, disease, and war from all the world, to the same extent they have already been eliminated from the developed nations. Although the analysis is approximate, the following conclusions seem inescapable:

8.2 The elimination of undernutrition, disease, and war, would require significant redirection of resources, including human resources, from wealthy to poorer nations.

8.3 The use of agricultural land for biodiesel production would not be possible until late this century, as all agricultural land would be required for food production.

8.4 The total amount of travel (excluding walking, bicycling, etc.) available to individuals would be limited. (Given present technology to, on average, less than 8000 km per person per year.)

[35] Food and Agriculture Organization of the United Nations statistical databases, FAOSTAT (http://apps.fao.org/page/collections).

8.5 Notwithstanding the limit in Conclusion 8.4, it would be necessary to use all of the world's remaining oil reserve for transportation purposes.
8.6 As well as using oil, some consumption of other fossil fuels for nontransportation purposes would also be necessary. Significant increase of atmospheric carbon dioxide concentration beyond present levels would therefore be unavoidable.
8.7 For the duration of this century, extending the amount of travel available to individuals beyond the limit in Conclusion 8.4, would require additional use of non-oil fossil fuels for transportation purposes, further adding to atmospheric carbon dioxide increase.

Given these conclusions, perhaps the best advice one could give a prospective passenger who is concerned about social and/or environmental issues, is that they review the purpose of their journey, and the quantity of travel they are consuming. If they are travelling to participate in the redirection of human resources (Conclusion 8.2), and/or if their journey will not extend them beyond their total travel allowance (Conclusion 8.4), then they may regard their journey as "green" and should not be overly concerned if the aircraft on which they fly is fuelled using fossil resources. Certainly, given these conclusions, the introduction of green air travel, supported using biodiesel, would seem a misguided development.

However, the situation is complex. Although it is depressing to contemplate given the time frame involved (a century), the world may lack the collective will for the redirection of resources mentioned in Conclusion 8.2 to occur. Undernutrition, disease, and war, would then persist in some poorer parts of the world, while agricultural surpluses continued to exist elsewhere. If that is destined to be the case, the introduction of flight on biodiesel, and its marketing as "green" air travel, might then be justified, as it would utilize agricultural resources which would otherwise be wasted, and assist the replacement of non-sustainable technology in the developed world.

The question of whether it is legitimate to market flight on biodiesel as "green" air travel is therefore complicated. There is urgent need for this issue to be debated, to either clear the way for implementation of a potentially useful tool to help the developed world reduce its dependence on non-sustainable technology, or to block the implementation of a potentially harmful scheme which could undermine global food security. Participants in the debate should include (among others):

- Representatives from groups concerned with changes in atmospheric carbon dioxide emissions, such as the Intergovernmental Panel on Climate Change (IPCC) (http://www.ipcc.ch/) and the United Nations Environment Programme (UNEP) (http://www.unep.org/).
- Representatives from groups concerned with global food security, such as the Food and Agriculture Organization of the United Nations (FAO) (http://www.fao.org/) and the United Nations Development Programme (UNDP) (http://www.undp.org/).
- Representatives from developing nations.

9. Conclusion

A preliminary analysis of the sale of green air travel supported using biodiesel suggests that it could be both technically feasible (Section 2) and commercially viable (Sections 4–7). However, it is not clear whether such a scheme is actually consistent with green objectives (Section 8). This is a complex question, involving environmental, humanitarian, resource management, and trade issues. It is a question which requires the urgent attention of the international political community, to either approve the introduction of a potentially useful tool to promote sustainable development, or to block a potentially dangerous scheme that could undermine global food security.

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Appendix A. Some statistics for commercial aviation

Aviation fuel accounts for 2–3% of total world fossil fuel consumption (~13% of fossil fuel consumption for transportation) [20]. Of the aviation fuel, approximately 15% is consumed by military aviation, approximately 2.5% by general aviation, and the remainder is consumed by commercial aviation [20]. For commercial aviation, the carriage of passengers (including their baggage) by scheduled airlines accounts for ~64% of all ton-kilometres performed [33]. In 1999, total world jet fuel consumption for transportation was 4.3 million barrels of oil per day (see footnote 10) (it is unclear if this includes a military component). Given these figures, the consumption of jet fuel for the carriage of passengers (including their baggage) by the world's scheduled airlines, is at least 854 million barrels of oil per year.

In 2000, the operating revenues of the world's scheduled airlines totalled approximately $328 billion [34]. For US scheduled airlines, passenger revenues in 2000 accounted for 72.3% of total operating revenues.[36] So, assuming the US airline industry is representative of the world airline industry, passenger revenues for the world's scheduled airlines are approximately $237 billion per year.

[36] Air Transport Association of America, Inc. (http://www.airlines.org/public/industry/bin/2001factfig.pdf)

Table 4
Details of two 737 flights across the Tasman

Route	Christchurch to Sydney	Sydney to Christchurch
Date of flight	7 August 2002	7 August 2002
Departure time (local time)	16:00 hours	19:00 hours
Cruise: altitude (feet)	34,000	35,000
mach	0.74	0.745
true air speed (knots)	435	439
indicated air speed (knots)	260	252
static air temperature (°C)	−50	−50
total air temperature (°C)	−26	−26

Appendix B. Fuel temperature data

This appendix summarizes some data, collected by Air New Zealand,[37] on the minimum fuel temperature encountered on board a Boeing 737-300 and a Saab 340A. Table 4 gives relevant parameters for two Boeing 737-300 flights, across the Tasman Sea, between Christchurch, New Zealand, and Sydney, Australia, a flight of some three and a half hours duration. Table 5 gives the fuel load and fuel temperature for the two flights. During the flights, the aircraft consumed fuel from three tanks, the left and right main tanks (one in each wing), and the centre tank (in the fuselage).

Table 5
Fuel load and fuel temperature for the two trans-Tasman, 737 flights summarized in Table 4

Route	Hours into flight	Fuel temperature (°C)	Fuel load (kg)		
			Left main	Centre	Right main
Christchurch to Sydney	Before departure	9.5	4550	2110	4550
	0.5	1.5	4500	0	4500
	1.0	−4			
	1.5	−10			
	2.0	−13			
	2.5	−13	2560	0	2520
	3.0	−11.5			
	End of flight	−1	1710	0	1710
Sydney to Christchurch	Before departure	14	4500	4600	4500
	0.5	14	4400	2940	4490
	1.0	2	4410	1780	4430
	1.5	−3	4410	510	4450
	2.0	−8	4230	0	4170

[37] Private Communication, Sarah Gorton, Malcolm Prebble, Bob Guard, all of Air New Zealand (Sarah.Gorton@airnz.co.nz).

The wing tanks each have a capacity of 4550 kg, and the centre tank a capacity of 6900 kg. The fuel in the centre tank has less thermal contact with cold, outside air, than fuel in the wing tanks, and is used first. The temperature probe is in the left main tank.

The minimum fuel temperature for the trans-Tasman flights was approximately −13 °C, considerably above the total air temperature (perhaps due to main tank fuel being used as a coolant for some aircraft systems).

The Saab 340A is similar to the Saab 340B (see Section 6.2.3). Table 6 shows data for a Saab 340A serving routes within New Zealand. During cruise in these flights, the true air speed was between 255 and 270 knots, and the indicated air speed was between 200 and 215 knots. The lowest minimum fuel temperature is seen to occur on the longest route (Auckland to Nelson), but is comparatively warm at −4 °C.

Appendix C. Oil reserves and consumption in the United States and European Union

The United States Geological Survey (USGS) has recently completed an assessment of the world's oil and gas resources.[38] The assessment involved more than forty geoscientists and took five years to complete (1995–2000). The assessment divides the resources (both oil and gas) into three categories, here referred to as:

RR Remaining reserves (resources already identified and awaiting extraction).
RG Reserve growth (resources not yet identified, but associated with already discovered fields).
UR Undiscovered resources (resources not yet identified, in fields not yet explored).

All data includes only those resources likely to be economically recoverable, given the technology likely to be available and economic conditions likely to exist between now and the year 2025. Unconventional oils are excluded (these will be mentioned briefly in Appendix D).

In this appendix, and Appendix D, "oil" includes natural gas liquids.

Using footnote 38, the value of RR + RG + UR for oil for the US, around the year 1996, is 32 + 76 + 83 = 191 billion barrels with an uncertainty of approximately +/−10%. For the EU nations the value of RR in 1999 was 7 billion barrels.[39] The USGS assessment does not include estimates of RG for each nation (only for the US and the world as a whole). Reserve growth depends on a number of factors, including the age of the fields involved (see footnote 38). Assuming EU fields are similar to US fields, a RG for the EU of approximately 16.6 billion barrels is calcu-

[38] US Geological Survey World Petroleum Assessment 2000, US Geological Survey Digital Data Series—DDS-60 (http://greenwood.cr.usgs.gov/energy/WorldEnergy/DDS-60/index.html).

[39] Survey of Energy Resources 2001, World Energy Council (http://www.worldenergy.org/wec-geis/publications/reports/ser/overview.asp).

Table 6
Data for flight operations with a Saab 340A (nm means nautical miles). Note that, when the plane was on the ground at Christchurch, there was a north-west wind (hence the comparatively warm air temperature)

Date	Route	Local time	Location	Flight level (feet)	True outside air temperature (°C)	Quantity of fuel on board (kg)	Fuel temperature (°C)
Aug. 24, 2002	Nelson to Christchurch	07:38		16,000	−11	900	+3
	Christchurch to Palmerston North	08:52	Top of climb	17,000	−15	1,000	+5
		09:10	Over Cape Campbell	17,000	−15	850	+2
		09:23	Top of descent	17,000	−13	750	0
	After refuelling	10:00	Palmerston North	Ground	+12	1,200	+9
	Palmerston North to Christchurch	10:24	Top of climb	16,000	−10	1,030	+4
		10:55	67 nm north of Christchurch	16,000	−14	840	+2
	After refuelling	12:20	Christchurch	Ground	+17	1,320	+17
	Chirstchurch to Nelson	12:50	33 nm north of Christchurch	15,000	−10	1,190	+8
		13:08	38 nm south of Nelson	14,000	−11	1,000	+5
Aug. 27, 2002	After refuelling	06:50	Napier	Ground	+7	1,100	+3
	Napier to Auckland	07:25	12 nm south of Rotorua	15,000	−15	900	0
		07:40	Top of descent, 56 nm east of Auckland	15,000	−14	800	−1
	After refuelling	08:26	Auckland	Ground	+9	1,600	3
	Auckland to Nelson	08:45	40 nm south of Auckland	16,000	−16	1,450	0
		09:25	70 nm north of Nelson	16,000	−19	1,000	−4

lated. Using footnote 38, UR for the EU are somewhere between 2.6 and 25 billion barrels. For the EU, the value of RR + RG + UR is therefore 37 billion barrels, with an uncertainty of +/−30%.

In 1996, US oil consumption was 6.7 billion barrels, and during the 1990s, consumption was increasing at a rate of approximately 1.6% per year.[40] Similarly, EU consumption was 4.8 billion barrels and was increasing at a rate of approximately 0.7% per year. Note that, in both cases, the increases in consumption are commensurate with population growth (see Appendix D).

Given these rates of consumption, and assuming no oil importation, the US and EU oil reserves would last 25 ± 3 years and 8 ± 2 years, respectively.

In 1990, the US satisfied 47% of its oil need by importation, and, during the remainder of the decade, this percentage grew steadily, reaching 57% by the year 2000.[41]

Appendix D. Lifetime of world fossil fuel resources

Conventional oil

Using footnote 38, the value of RR + RG + UR (see Appendix C) for oil, for the world, in 1996, was somewhere between 1700 and 3700 billion barrels, with a most likely value of about 2600 billion barrels.

In the year 1996, the world consumed 26.1 billion barrels of oil (see footnote 40). At this rate of consumption, the world oil reserve would be exhausted at some stage between the years 2061 and 2138, most likely around the year 2096. Any increase in the rate of consumption would bring forward these dates. During the 1990s, the rate of consumption was increasing steadily by about 1.6% per annum (see footnote 40). This increase reflects two factors.

The first factor is a growing world population. In 1996 the world population was 5.74 billion and, during the 1990s, the population was increasing steadily at a rate of 1.4% per annum (see footnote 35). How the population will continue to grow is uncertain. The United Nations predicts that, in 2050, the population will be somewhere between 7.7 billion (and static) and 11.2 billion (and still growing) [29]. Nearly all of the forecast growth is expected to occur in the developing world.

[40] International Energy Annual 2000. Report number DOE/EIA-0219(2000), see footnote 9, (http://www.eia.doe.gov/emeu/iea/iea2000.html). In particular, Table 1.2 (http://www.eia.doe.gov/pub/international/iealf/table12.xls).

[41] Annual Energy Review 2000. Report number DOE/EIA-0384(00), see footnote 9 (http://www.eia.doe.gov/emeu/aer/contents.html). In particular, Table 5.1 (http://www.eia.doe.gov/emeu/aer/txt/tab0501.htm).

The second factor is increasing oil consumption in the developing world. Fig. 9 shows a breakdown of the world's people, by nation, according to oil consumption. People are distributed along the horizontal axis, with people from the oil poorest nations (nations with lowest oil consumption per capita) to the left. The right hand edge of the figure coincides with the total world population. The vertical axis indicates the oil consumption of each person, obtained by dividing the oil consumption of each nation (footnote 40) by the nation's total population (see footnote 40, Table B1). The data is for the year 2000. Note that Luxembourg, Kuwait, Qatar, the UAE, Singapore, and a number of small, island nations, all consume more than 27 barrels per person per year (top right hand side of graph). However, taken globally, they represent neither a significant number of people, nor a significant total oil consumption. Otherwise the right hand side of the graph is dominated by the United States (281 million people, or 4.6% of the world population, consuming 25.6 barrels per person per year), Japan (127 million people, or 2.1% of the world population, consuming 15.9 barrels of oil per person per year), and the European Union (376 million people, or 6.2% of the world population, consuming, on average, 12.9 barrels per person per year, with no nation below 10.5 barrels per person per year). For these nations, the oil consumption per person is approximately static, as shown by Fig. 10. However, in much of the developing world, oil consumption per person is increasing, as shown in Fig. 10 for China and India (21% and 16.5% of total world population, respectively, in the year 2000).

In Fig. 9 the total population is 6.1 billion people and the total oil consumption is 27.7 billion barrels per year. If those nations with consumptions less than 4 barrels per person per year are assumed to develop such that their consumption is increased to 4 barrels per person per year (dashed line in Fig. 9), while the consumption of other nations is unchanged, then the total consumption grows to 39.7 billion barrels per year. Adding another 1.6 billion people, also consuming 4 barrels per person per year, increases the total consumption to 46.1 billion barrels per year. This would seem the absolute minimum consumption to plan for, for the year 2050 (the

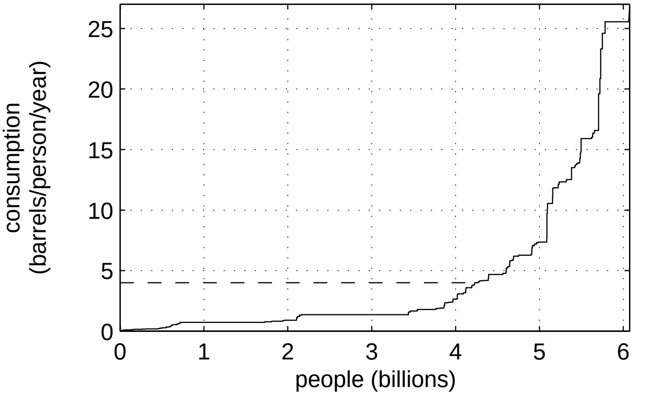

Fig. 9. Breakdown of the world's people, by nation, according to oil consumption for the year 2000. The dashed line indicates consumption at a level of 4 barrels of oil per person per year.

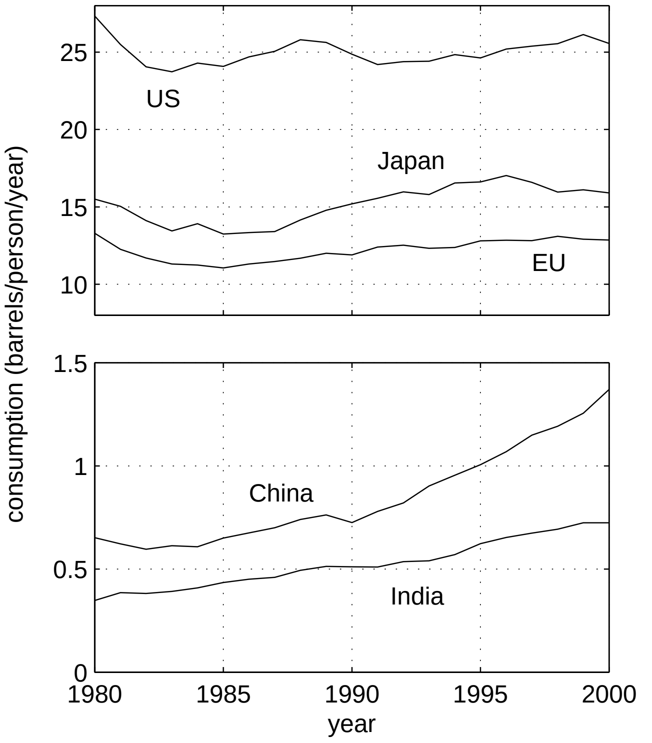

Fig. 10. Oil consumption per person per year for the US, Japan, EU, China and India.

additional 1.6 billion people increase the world population to the UN minimum estimate for that year of 7.7 billion, and 4 barrels of oil per person per day is still less than 1/3 the consumption in the EU and less than 1/6 the consumption in the US). Assuming the consumption grows linearly from 26.1 billion barrels per year in 1996 to 46.1 billion barrels per year in 2050, and then remains static, the world RR + RG + UR of oil would be exhausted somewhere between 2044 and 2088, most likely around the year 2064.

Other fossil fuel resources

In addition to conventional oil, the world has reserves of natural gas, unconventional oil (oil shale, natural bitumen and extra-heavy oil) and coal. To some extent these fuels are interchangeable. For example, kerosene type liquids, for use in aviation turbine engines, can be obtained from natural gas, unconventional oil and coal by suitable chemical processing [3,18,35–37], and there is already some production of such fuel by Sasol Oil [38] (see also [2]). It is therefore of interest to investigate how long the fossil fuel resource (irrespective of type) will last.

Using footnote 38, the value of RR + RG + UR (see Appendix C) for natural gas,

for the world, in 1996, was somewhere between 1500 and 3200 billion BOE, with a most likely value of 2300 billion BOE.

The world reserve of oil shale is distributed worldwide and exceeds that of conventional oil (see footnote 39). However, at the present time, the large scale utilization of this reserve is prevented by a combination of economic and environmental barriers.

The world's reserves of natural bitumen and extra-heavy oil are dominated by a single deposit in each category (see footnote 39). The bitumen deposit is in Canada and the extra-heavy oil deposit is in Venezuela. Together, these two deposits are equivalent to about 3600 billion barrels of oil. Both are currently in commercial production. The amount of the resource which may ultimately be recovered is uncertain, but a figure of 5% is not unreasonable.

In 1999, the world proved recoverable reserves of bituminous coal (including anthracite), sub-bituminous coal and lignite were 519, 276 and 189 billion tons, respectively (see footnote 39). In addition to this, there were estimated additional reserves recoverable of at least 149, 51 and 209 billion tons (also respectively). Assuming a ton of bituminous coal or anthracite is equivalent to 4.2 barrels of oil, a ton of sub-bituminous coal is equivalent to 3.4 barrels of oil, and a ton of lignite is equivalent to 2.2 barrels of oil, this gives a total coal reserve of 4800 billion BOE.

Hence, a reasonable estimate for the world total fossil fuel reserve remaining to be utilized, as at the late 1990s, is 9880 billion BOE.

In 1996, world total consumption of all types of fossil fuels was 55 billion BOE, and was increasing at a rate of approximately 1.4% per year (see footnote 40, Tables E2, E3 and E4). A breakdown of the world population, according to fossil fuel consumption per person, for the year 2000, looks qualitatively very similar to Fig. 9. It therefore seems sensible to assume, in analogy with the scenario for oil in *Conventional oil*, that the total fossil fuel consumption will increase linearly, from 55 billion BOE in 1996, to 97 billion BOE in 2050, and thereafter remain constant. Assuming this consumption, the reserve of 9880 billion BOE would be exhausted around the year 2108.

Appendix E. Vegetable oil production in the US and EU

In 1999, US jet fuel consumption for transportation was ~1.7 million barrels of oil per day (see footnote 10). Assuming the utilization of jet fuel for transportation in the US is similar to that in the world as a whole (see Appendix A), the consumption of jet fuel in the US by scheduled airlines for the carriage of passengers (including their baggage) is at least 338 million barrels of oil per year. If green air travel accounted for 1% of all air travel sold (Section 7), commercial aviation in the US would require $\sim 0.01/\Gamma \times 338$ million barrels of biodiesel per year, where $\Gamma = 0.66$ (see Section 6.1). This is 215 million gallons of biodiesel per year, very much larger than current US biodiesel production (~20 million gallons per year—see Section 2.2). However, production of 215 million gallons of biodiesel requires the oil of ~3.4 million tons of soybeans (see footnote 20), and, during the 1990s, the US was a net exporter of approximately 20 million tons of soybeans per year, with an increas-

ing trend (see footnote 35). Furthermore, this export far exceeded US import of all other oilseeds and oilseed oils (see footnote 35).

In 1999, EU jet fuel consumption for transportation was ~0.7 million barrels of oil per day (see footnote 10). If green air travel accounted for 1% of all air travel sold, commercial aviation in the EU would require 89 million gallons of biodiesel per year, which, in turn, would require 0.3 million tons of soybean oil per year (see footnote 20). During the 1990s, the EU was a net exporter of both soybean and rapeseed oils, with net exports of both oils averaging approximately 0.7 million tons per year (see footnote 35).

Hence, both the US and EU could satisfy demand for flight on biodiesel from domestic resources.

Appendix F. Price premium and market share for green electricity

As mentioned in Section 7, price premium and market share data for green electricity was collected for a subset of US electricity vendors. US vendors were chosen, partly because an up-to-date summary of all green electricity programs in the US was available (see footnote 33), and partly because a considerable amount of data for sales of conventional electricity by US vendors was freely available in the public domain.[42] In order to obtain data which would be relevant for predicting the market share for green air travel, data was collected only for vendors approximately satisfying the following criteria:

1. Captive customer base: Up until the late 1990s, US vendors had a monopoly to supply electricity to all consumers within their service territories. This remains the case in some areas. However, in other areas, the electricity industry has been restructured and consumers can now purchase electricity from among competing retailers (see footnote 42). It was decided to exclude vendors trading in competitive environments because the consumers in those environments have had to cope with the introduction of both retail competition and green electricity, and the former may have distracted consumers' attention from the latter. Hence, data was collected only from vendors operating in a monopoly situation, either because they were in areas yet to restructure, or because they were in areas which, although restructured, had yet to experience any significant competition from the arrival of new retailers.
2. Large customer base: Smaller vendors were excluded, as their customer base might not be representative of the population as a whole.
3. Ideally the vendor would generate electricity predominantly by burning oil, as the concerns raised by this technology most closely resemble Concerns 3.1–3.4 in Section 3. However, in the US, oil fired power stations are rare, the bulk (more

[42] Electric Sales and Revenue 2000, see footnote 9, http://www.eia.doe.gov/cneaf/electricity/esr/esr_tabsh.html.

than half) of all electricity being generated by the combustion of coal.[43] In the US, Concerns 3.1 and 3.4 are far less applicable to the combustion of coal than they are to the combustion of oil. (In 1999, the US proved recoverable reserve of coal was 250 billion tons (see footnote 39). In the same year, US coal consumption was 947 million tons (see footnote 39). With this rate of consumption, the US has adequate coal to last more than 250 years. This should be compared to the figure for oil in Appendix C). The use of nuclear power is undesirable, as it raises concerns for which flight on kerosene has no analogues.

4. Nature of program: Vendors should sell both conventional electricity and green electricity by the kWh, and consumers should be able to specify the fraction of electricity they purchase (fraction of kWh) they wish to be green. The program should be open to both business and household consumers. These are to ensure similarity with the proposed sale of green air travel (see Fig. 4).
5. Duration and stability of program: Vendors should have been selling green electricity for at least three years and not made significant changes to their green electricity programs during that time. This was to ensure sufficient time for the market share of green electricity to reach a steady state value.
6. Adequate supply of green electricity: At the end of the period mentioned in 5, the vendor should have had sufficient capacity to supply at least as much green electricity as was being demanded by consumers. If, at any time during the period, demand exceeded supply, customers should have been placed on waiting lists and then supplied with green electricity when new generating capacity became available. This was to ensure market share for green electricity was not restricted by shortage of supply.
7. Adequate supply of conventional electricity: During the period mentioned in 5, the vendor should not have experienced any shortage in the supply of conventional electricity (again, this might distort the market share for green electricity).

Using reference [31], footnotes 33 and 42, and the web pages of vendors, eight vendors were identified that approximately satisfied the seven criteria. Data for the sale of green electricity was requested from all eight vendors. Three of the vendors (Colorado Springs Utilities, Indianapolis Power and Light, and Wisconsin Electric Power) would not supply data. A summary of data for the remaining five is given in Table 7, and further details follow. For convenience, the five are referred to by the names of the states in which they operate. As indicated in Table 7, two of the vendors had a nuclear component, otherwise all five were dominated by generation using coal (see footnote 43).

Colorado

Between 1998 and 2002, the Public Service Company of Colorado became part of Xcel Energy. In requesting data from Xcel, it was made clear that the data should

[43] Electric Power Annual 2000, Volume I, Table 7. Report number DOE/EIA-0348(2000)/1, footnote 9 (http://www.eia.doe.gov/cneaf/electricity/epavl/ generation.html#tab7).

Table 7
Data for five US electricity vendors

Name of vendor		Dakota Electric Association[a]	Public Service Company of Colorado[b]	Dairyland Power Cooperative[c]	Lincoln Electric System[d]	Arizona Public Service[e]
State		Minnesota	Colorado	Wisconsin	Nebraska	Arizona
Profile for sale of conventional electricity:						
Nuclear content of fuel mix		None[f]	None[g]	None[h]	~17%[i]	~37%[j]
Number of residential consumers		79,391[k]	1,008,211[k]		96,781[k]	744,124[k]
Quantity of electricity sold (GWh) & average sale price (cents per kWh)	Residential	733 & 7.66[k]	7,486 & 7.37[k]	2,193[h] & see text	974 & 6.10[k]	9,769 & 9.01[k]
	Commercial	284 & 6.78[k]	12,025 & 5.34[k]	1,462[h] & see text	1,002 & 4.56[k]	10,045 & 7.68[k]
	Industrial	443 & 4.39[k]	4,727 & 4.13[k]		560 & 3.86[k]	2,598 & 5.85[k]
	Year	2000	2000	2001[h]	2000	2000

(*continued on next page*)

Table 7 (*continued*)

Name of vendor		Dakota Electric Association[a]	Public Service Company of Colorado[b]	Dairyland Power Cooperative[c]	Lincoln Electric System[d]	Arizona Public Service[e]
Green electricity program:						
Name		Wellspring[a]	Windsource[b]	Evergreen[c]	Renewable Energy Program[d]	Solar Partners[e]
Introduced		Feb. ’99[l]	1998[g]	1998[h]	1998[i]	1996 [31]
Price premium		~20%	~42%	~43%	~88%	~120%
Total green electricity sold (MWh)	Residential	238.3[l]	8,650[g]	2,400[h]	199.4[i]	87.5[m]
	Com.&indust.	38.5[l]		Nil		
	Time Period	April ’02[l]	April ’02[g]	Year 2001[h]	March ’02[i]	March ’02[m]
Market share		~0.23%	~0.43%	~0.072%	~0.094%	~0.0047%

[a] http://www.dakotaelectric.com
[b] http://www.xcelenergy.com/
[c] http://www.dairynet.com/
[d] http://www.les.com/
[e] http://www.aps.com/. Note that APS is a subsidiary of Pinnacle West Capital Corporation, http://www.pinnaclewest.com/
[f] Private communication, L. Landwehr, Dakota Electric Association (Landwehr@dakotaelectric.com).
[g] Private communication, C.A. Sulkko, Xcel Energy (Andy.Sulkko@XCELENERGY.COM).
[h] Private communication, C. Harmes, Dairyland Power Cooperative (cth@dairynet.com).
[i] Private communication, R. Reno, Lincoln Electric System (RReno@les.com).
[j] Pinnacle West Capital Corporation Statistical Report 2000, p. 84–90 (http://www.pinnaclewest.com/annual/pdfs/aps_operating.pdf).
[k] Footnote 42, Tables 14–16.
[l] Private communication, C. Sampson, Dakota Electric Association (csampson@dakotaelectric.com)
[m] Private communication, P. Johnston, Pinnacle West Capital Corporation (Peter.Johnston@pinnaclewest.com).

relate to those customers in the former service area of the Public Service Company of Colorado.

Colorado sold green electricity in 100 kWh blocks. The purchase of each 100 kWh block added $2.50 to a customer's bill (see [31] and Table 7, footnote b).

The average price of electricity sold to each sector (residential, commercial and industrial) for Colorado, listed in Table 7, is the total revenue the company earned from that sector, divided by the total quantity of electricity (kWh) the company delivered to that sector. The same is true for Minnesota, Nebraska and Arizona. Note that, since green electricity constitutes such a small amount of total electricity sales, the values are essentially those for sales of conventional electricity. As well as earning revenue from the sale of electricity on a kWh basis, the companies also earned revenue from electricity sales on a capacity (kW) basis, from connection charges, and so on. In the case of Colorado, if customers, from any sector, purchased electricity on a per kWh basis, they did so at a rate of ~6 cents/kWh,[44] and it is this value which has been used for the price of conventional electricity in calculating the price premium for green electricity.

Nebraska

From 1998 to March 2002, Nebraska sold green electricity in 100 kWh blocks, with each customer purchase of a 100 kWh block adding $4.3 to the customer's bill (see Table 7, footnote i).

Nebraska charges residential consumers a "Customer & Facilities Charge" of $6.00/month, and otherwise charges residential consumers by the kWh (see Table 7, footnote d). Subtracting the revenue from the customer and facilities charge from the total revenue from residential consumers, the average sale price of electricity to residential consumers is computed to be 5.38 cents/kWh. In the case of commercial consumers, the monthly customer and facilities charge varies between $7.65 and $22.65 (see Table 7, footnote d). A similar calculation then gives ~4.33 cents/kWh as the average sale price of electricity to commercial consumers. Hence, in calculating the price premium for green electricity, 4.9 cents/kWh has been assumed for the sale price of conventional electricity.

Fig. 11 shows a graph of total monthly sales of green electricity (see Table 7, footnote i) verses time. Note that, for Nebraska, sales are currently declining. This will be reflected in a declining market share for green electricity (although the rate of decline is slow).

Arizona

When introduced in 1996, Arizona's program was of the capacity type [31]. In August 1999, the program was amended to the sale of 15 kWh blocks of green electricity at a price of $2.64 per block.[45]

[44] http://www.xcelenergy.com/EnergyPrices/colorado/psco_elec_entire_tariff.pdf

[45] Arizona Public Service Company Electric Rates, p. SP-1, August 1999 (http://www.aps.com/images/pdf/sp-l.pdf).

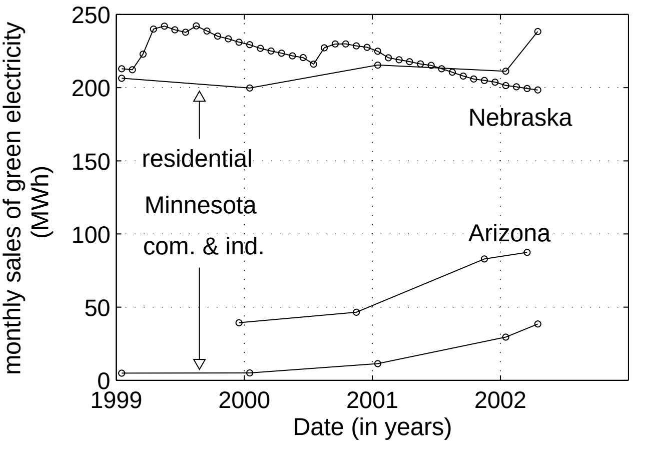

Fig. 11. Trends in the monthly sales of green electricity over time for three of the vendors in the study.

Arizona charges residential consumers a “Basic Service Charge” of $7.50 per month.[46] Subtracting this from the revenue the company receives from its residential consumers (see *Nebraska*), the value at which conventional electricity is sold to residential consumers is found to be 8.32 cents/kWh. For commercial consumers, the Basic Service Charge is $12.50 per month,[47] and the corresponding value at which conventional electricity is sold to commercial consumers is found to be 7.54 cents/kWh. Hence, in calculating the price premium for green electricity, the price of conventional electricity has been taken as 8 cents/kWh.

Total monthly sales of green electricity for Arizona (see Table 7, footnote m), are also shown in Fig. 11.

Retail choice was introduced to customers within Arizona’s service territory between October 1999 and January 2001 (see Table 7, footnote j). However, as at March 2002, the advent of restructuring had not impacted significantly on Arizona’s customer base.

Minnesota

Minnesota sold green electricity in 100 kWh blocks, with each customer purchase of a 100 kWh block adding ~$1.31 to the customer’s bill (this number varied by +/−7% during the period of the study) (see Table 7, footnote l).

Note that, for Colorado, Nebraska and Arizona, the value for the price of conventional electricity, used in calculating the price premium for green electricity, is ~15%

[46] Arizona Public Service Company Electric Rates, p. E-12, July 2001 (http://www.aps.com/images/pdf/e-12.pdf).

[47] Arizona Public Service Company Electric Rates, p. E-32, July 2001 (http://www.aps.com/images/pdf/e-32.pdf).

lower than the average sale price for residential consumers listed in Table 7. It is assumed that the same holds for Minnesota, and a value of 6.5 cents/kWh has been assumed for the per kWh price of conventional electricity in the case of Minnesota.

Total monthly sales of green electricity for Minnesota (see Table 7, footnote l), are also shown on Fig. 11.

Wisconsin

Wisconsin sold green electricity in 100 kWh blocks, with each customer purchase of a 100 kWh block adding $3.00 to the customer's bill (see Table 7, footnote h). Note that only residential consumers were eligible to participate in the program.

The average sale price for conventional electricity was obtained from Wisconsin as 7 cents/kWh (see Table 7, footnote h). It is not clear precisely how this has been calculated, and it has been used without modification in calculating the price premium for green electricity.

At the end of 2001, Wisconsin had approximately 1000 customers purchasing green electricity and a further 100 on a waiting list (see Table 7, footnote h). If it is assumed that the average customer on the waiting list would purchase the same number of 100 kWh blocks as the average customer already participating in the program, then Wisconsin would be selling ~2640 MWh/year of green electricity. This value has been used in calculating the market share for green electricity.

Appendix G. Allocation of agricultural and fossil fuel resources

The purpose of this appendix is to determine how the world's resources of fossil fuels and agricultural land would need to be allocated, under the assumption that, during the course of the century, the sufferings associated with undernutrition, disease and war are to be eliminated from all the world's people, to the same extent that they are already eliminated from the developed world. In addition, it will be assumed that development is to occur in such a way as to maximize the availability of transportation fuels (assumed to include fuels suitable for commercial aviation). In this way, some indication of the maximum amount of air travel compatible with the elimination of suffering, can be inferred.

The elimination of undernutrition, disease, and war, would require that all the world's people be empowered to participate in education and society. Without such participation, history strongly suggests that human populations continue to grow until the growth is restrained, either by war, by disease, or by resource depletion (encompassing undernutrition). Currently there is a large number of people in poorer nations who do not have access to education and/or do not have free time to participate in society. The provision of education for these people requires human resources to be transferred from wealthier to poorer nations, for example, the deployment of teachers and training programs. The provision of free time also requires the transfer of human resources from wealthier to poorer nations, in the form of the development

and deployment of appropriate technologies, such as pumps and filters to supply clean water. The provision of free time also requires that all the world's people have access to energy resources, such as transportation fuels for agricultural machinery and the transportation of food. Without energy resources, everything must be done manually, which can severely limit free time.

At the present time, the world population is just in excess of 6 billion (see footnote 35). How the population will grow is uncertain. The United Nations' projections for the year 2050 vary between 7.7 billion and 11.2 billion [29]. From the point of view of maximizing fuel production for air travel, a smaller population is desirable (fewer people means less land needed for food production, which, in turn, means more land available for biodiesel production). However, undernutrition, disease, and war, all reduce population, so, if these are to be eliminated, the UN minimum population projection would seem unlikely. As a compromise, the median UN population projection will be used. The median projection is that, in the year 2050, the population will be 9.4 billion, and still growing slowly [29]. The growth will be ignored, and the population will be assumed to remain static for the next generation (25 years). In subsequent generations, the population will be assumed to drop by a factor of two per generation (consistent with the global adoption of a one child per family policy). It is difficult to envisage that the global population could be reduced more rapidly than this without infringing human rights (the right to experience parenthood) and without causing undue social strain (for example, a very disproportionate number of older people in comparison to those of working age). The world population as a function of time for the scenario is plotted in Fig. 12.

The land area of the Earth is 13 billion hectares (see footnote 35). The agricultural area is currently 5 billion hectares (see footnote 35). Note that "agricultural area"

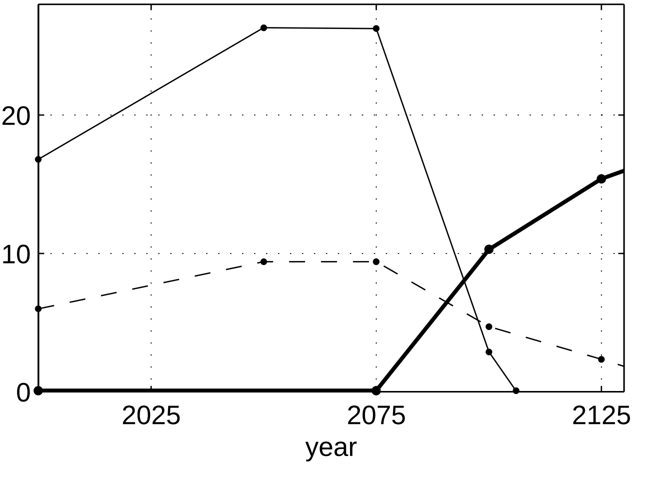

Fig. 12. Population (dashed line), net biodiesel production (thick line), and oil consumption (thin line), for the scenario in Appendix G. The population is in billion people, and the biodiesel production and oil consumption are both in billion BOE per year.

includes land used for food production, land used for some non-food crops, such as cotton and rubber (of which the biodiesel contribution is currently negligible), but excludes land under trees grown for wood or timber. Subsequently, "food production" is taken to mean both the production of food, and the production of non-food, non-biodiesel crops.

It will be assumed that the size of the agricultural area remains fixed at 5 billion hectares. This is the land area available for biodiesel and food production.

Currently world food production exceeds world food demand by approximately 10% (although some 700 million people still suffer from chronic undernutrition, due to problems with the distribution of food) [29]. It will be assumed that, between the present time, and the year 2050, there will be improvements in agricultural yield and the distribution of food, so that, in the year 2050, 9.4 billion people can be adequately fed with 5 billion hectares of agricultural land. It should be pointed out that this represents a difficult technical challenge. During this time, there will be no land available for biodiesel production. In 2050, the land area required for food production per person would therefore be 0.53 hectares. It will be assumed that, subsequent to 2050, this figure remains static. After the year 2075, as the population declined, it would no longer be necessary to use all of the agricultural area for food production. It will be assumed that all surplus area is used for biodiesel production. In Germany, biodiesel production from rapeseed requires an energy input of 22.3 GJ per hectare per year and yields 47.8 GJ of biodiesel per hectare per year [6]. Assuming the energy input is derived from biodiesel, the net yield of biodiesel is therefore 4.1BOE per hectare per year. It will be assumed that the same yield can be achieved with the agricultural area surplus to food production requirements after the year 2075. This is probably optimistic, as much of the world's agricultural area, would be of lower agricultural productivity than that found in Germany. With these assumptions, world biodiesel production then appears as shown in Fig. 12.

In 1995, the world total energy consumption was 60 billion BOE [29]. Assuming the transportation sector derived all its energy from fossil fuels (i.e. electric rail was negligible[48]), ~62% of the total consumption was consumption of fossil fuels for non-transportation purposes, such as electricity generation, steel production, domestic heating, and so on. In order to maximize the fuel available for transportation, it will be assumed that fossil fuel consumption for non-transportation purposes does not use oil and decreases linearly from 37.2 billion BOE per year at the present time, to zero in the year 2050. This represents a total consumption of 930 billion BOE (most likely ~40% of the world natural gas reserve—see Appendix D, *Other fossil fuel resources*). It should be emphasized that, in practice, this would be very difficult to achieve. Although it could be argued that consumption in the developed world is already excessive and could be reduced, in parts of the developing world consumption is already very low (see Appendix D), and, as mentioned in the second paragraph, there is a need to provide energy to these areas. In addition,

[48] In the EU, for example, electricity accounts for ~1% of the energy used by the transportation sector. See [39].

the population will be growing during this time, adding more people, all of whom must be provided with energy. So it is not acceptable to simply stop the consumption of fossil fuels, some replacement must be found. At this stage, it is not clear if the human race could obtain such a large energy resource from other, practical technologies, such as nuclear, hydro, and wind power.

In order to maximize the fuel available for transportation, it will also be assumed that any non-energy fossil fuel requirements (such as petrochemicals) can be met from coal and gas, without using oil.

Given the objective of eliminating undernutrition, disease and war, it becomes possible, at least in principle, to classify all transportation as either *essential* or *non-essential*. Examples of *essential* transportation would be the transportation of food from producers to market, and the transportation associated with construction and maintenance of basic infrastructure. In practice, classifying any particular transportation as either essential or non-essential might prove problematic, but, at least conceptually, the distinction exists. It will also prove useful to distinguish between the consumption of transportation by *household* consumers, and the consumption of transportation by *non-household* consumers. The division of transportation into its various categories, together with an example of each, is shown in Fig. 13. Note that some household consumption is essential (for example, the transportation of a sick child to see a doctor) and some is work related (specifically, transportation between home and workplace).

In 1995, 26% of world total energy consumption was used by the transportation sector [29] and the world population was 5.66 billion (see footnote 40, Table B1), giving a global average energy consumption for transportation of 2.8 BOE per person per year. As might be expected from Fig. 9, the distribution among nations was highly uneven, the US, for example, consuming 15.4 BOE/person/year, and China and India consuming 0.36 and 0.20 BOE/person/year, respectively.[49]

As already discussed, if undernutrition, disease and war are to be eliminated, all the world's people must have access to sufficient energy to satisfy their essential transportation requirements. Estimating the amount of energy required is difficult.

	Essential	Non-essential
Household	Use of a family car to take a sick child to see a doctor.	Flying overseas for a holiday.
Non-household	Transportation of food from producers to market.	Transportation of a professional sports team to participate in an away game.

Fig. 13. The division of transportation into four categories according to whether it is essential or non-essential and whether it is consumed by households or non-households, including an example of each. Note that, in practice, the boundaries between categories are probably somewhat blurred (especially in the case of the essential/non-essential boundary).

[49] Country Analysis Briefs, footnote 9 (http://www.eia.doe.gov/cabs/).

Appendix H briefly attempts to determine if a national allowance of 2.8 BOE/person/year would be sufficient. The results are inconclusive. For the present scenario, it will be assumed that 2.8 BOE/person/year *is* sufficient, and that, from the present time onwards, all nations will have access to this quantity of energy for transportation, and no more. In other words, the world would continue to consume energy for transportation at the present rate, but the energy would be shared equally among the world's nations. For the developed nations, this would represent a large reduction in energy for transportation. In particular, Appendix H suggests that the total powered transportation available for household consumption would be only 8000 km/person/year. Note that this must include essential household transportation, so the amount of transportation available for recreational purposes would be significantly less. Such limited availability of household transportation would result in significant reductions in air travel. Intercontinental travel, in particular, would seem destined to become a once in a lifetime opportunity for most people.

Given all these assumptions, in the year 2106, the population would decline to 4.1 billion, and, at that time, the world would be able to satisfy its energy requirement for transportation using biodiesel. Between the present time and that year, the energy required for transportation would come in part from fossil fuels. Assuming the fossil fuel used for transportation is oil, the consumption of oil then appears as shown in Fig. 12. The total oil consumption between the years 2000 and 2106 is then calculated to be 2110 billion barrels (most likely ~85% of the world oil reserve—see Appendix D, *Conventional oil*).

In the 1990s, the concentration of atmospheric carbon dioxide was approximately 365 ppm, and was increasing at a rate of 1.5 ppm per year, due to the emission of 6.3 Gt of carbon per year [22] (note that combustion of fossil fuels accounts for ~96% of world total carbon dioxide emissions [29]). Assuming 1BOE contains 118 kg of carbon, combustion of 930 billion BOE (for non-transportation purposes) and 2110 billion BOE (for transportation) would be expected to raise the concentration of atmospheric carbon dioxide to approximately 450 ppm (the pre-industrial concentration was about 280 ppm [22]).

It should be emphasized that the calculations have been based only on the assumptions that undernutrition, disease, and war are to be eliminated, and that resources should be directed towards production of transportation fuels where possible. No attempt has been made to extend the high level of material wealth currently enjoyed by people in the developed world, to people in the developing world, or even to preserve the levels in the developed world. In addition, many of the assumptions made regarding what can be achieved in population management, agricultural yield, and energy technology, have been highly optimistic. Despite this, it seems likely that the entire world oil reserve would be needed for transportation and that the amount of travel available to individuals would need to be limited (given current technology, to about 8000 km per person per year). For the duration of this century, any attempt to extend beyond the limit would require the additional use of non-oil fossil fuels by the transportation sector, further adding to an already substantial rise in atmospheric carbon dioxide concentration.

Appendix H. Energy for transportation

The scenario in Appendix G assumed that each nation would be allocated liquid fuels for transportation, equal in quantity to 2.8 BOE/person/year (a reasonable allocation, given estimated oil reserves and concerns over atmospheric carbon dioxide increase). As mentioned in Appendix G, if undernutrition, disease and war are to be eliminated, all nations must have access to some quantity of liquid fuels for essential transportation (see Appendix G, especially Fig. 13, for clarification of "essential"). The purpose of the present appendix is to try and estimate if 2.8 BOE/person/year is likely to be sufficient. A secondary purpose is to try and estimate how much transportation would be available to household consumers, given a national allowance of 2.8 BOE/person/year (again, see Appendix G for clarification of "household consumption").

Table 8 shows the energy consumption for transportation (total energy consumed by the transportation sector divided by national population) for a number of countries. Each value is for one of the years 1998 through 2000, and some values are estimates. The countries were selected using references [29] and [40], and footnote 49 as a guide. The US was selected as, excluding some small nations, it has the largest energy consumption for transportation per capita. The UK was included as representative of an EU nation (excluding Luxembourg and Portugal, the other EU nations all had energy consumptions for transportation in the range 6.3–8.7 BOE/person/year (footnote b, Table 8)). The remaining nations are those for which statistical data was readily available, and for which the energy consumptions for transportation were close to the allocation of 2.8 BOE/person/year.

Table 8 also gives values for population density (of interest, since it might partly determine essential transportation requirement), undernutrition, under-five mortality rate (which reflects a number of factors, including access to clean drinking water, nutrition, incidence of infectious disease, and so on), total fertility rate (which gives a measure of the propensity of the national population to expand or contract), the gross enrollment ratio for secondary education (which gives some indication of the state of education), and the ratio of wealth between rich and poor (of relevance to air travel, since the household consumption of air travel might depend on the presence of a wealthy elite). With the exception of the ratio of wealth for the UK, which is for the year 1991, each data is for some time period between 1996 and 2000.

Of the countries in Table 8, the Central European countries (CZ and HU) do seem largely free of undernutrition, disease and war. Hence, it seems possible for some countries to eliminate these problems, while only using energy for transportation of ~2.8 BOE/person/year. However, in the Latin American countries (MX, AR and CL) these problems persist (MX and CL still have significant undernutrition, and AR has recently experienced a period of great economic and political instability). What is of interest is whether the Latin American countries could achieve the same level of success as the Central European countries while still only using energy for transportation of ~2.8 BOE/person/year. One difficulty they might encounter is that their essential transportation requirement might be greater than that of the Central European countries (the Central European countries are located in part of the world which

is intrinsically compact). Further insight can be gained from how the development indicators for the Latin American countries have been evolving in recent decades. The ratios of wealth between rich and poor have been approximately static [43]. All the other development indicators have been improving (which gives reason for optimism), with one exception—the percentage of the population in Mexico which is undernourished has been static for the last twenty years (see Table 8, footnote d).

Level of development is influenced by many factors, of which energy for transportation is only one, and it is difficult to reach any definitive conclusions. Nevertheless, given the example of Mexico, it seems dangerous to conclude that an energy allocation for transportation of ~2.8 BOE/person/year will be sufficient. It may well be that, for some nations, such an allocation would not be adequate to eliminate the basic problems of undernutrition, disease and war.

Turning now to the problem of how much transportation might be available to household consumers, assuming an allocation of 2.8 BOE/person/year, Table 9 gives some transportation statistics for the same countries in Table 8. The objective is to give some insight into the division of transportation, both between household and non-household consumption, and between some different modes (private road vehicle, air, and public road and rail). Note that each data is for some time interval within the years 1996–2001. The household consumptions/expenditures, in particular, are for an interval within the years 1996 and 1997, except for the data for CZ, which is for the year 2001 (comparisons between countries are weakened somewhat, if the data for different countries relates to different years, due, for example, to the effects of changes in the price of oil).

Fig. 14 has been constructed from the data in Table 9. In constructing the figure, the following assumptions have been made:

1. That the household consumption of private road vehicle travel is proportional to the household consumption of motor fuel and the average number of persons per household. Values for household consumption of private road vehicle travel for the non-US countries can then be calculated from the US value.
2. That that ratio of household consumption of jet fuel and household expenditure on airfares is the same for all nations. This allows household consumptions of jet fuel for the non-US countries to be obtained by scaling the US value according to household expenditures on airfares.
3. That the argument in 2 also applies to the ratio of household consumption of air travel and household expenditure on airfares.
4. That, for all nations, all of the public transportation is consumed by households.
5. That, for all nations, the average energy intensity for public transportation is 0.3 BOE per thousand passenger-km, which is approximately correct for the US[50] (see also Table 3, footnote b) [134], [65].

[50] In the US, the energy intensities of automobiles, certified air carriers, transit buses, intercity buses, transit rail, and intercity rail are 3700, 4000, 4200, 900, 3200 and 2400 Btu per passenger-mile, respectively (see Table 9, footnote d). Note that 4000 Btu per passenger-mile equals 0.42 BOE per thousand passenger-km.

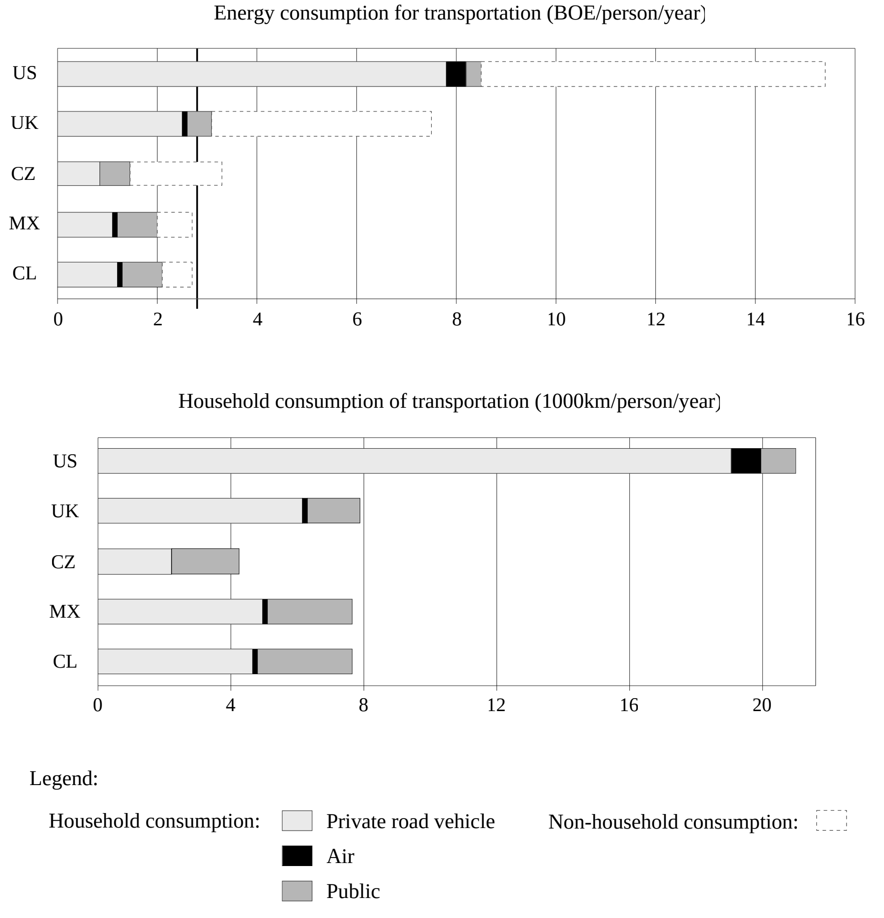

Fig. 14. Energy consumption for transportation (upper) and household consumption of transportation (lower) for five of the countries in Tables 8 and 9. The allocated energy consumption of 2.8 BOE/person/year is shown by the bold, vertical line in the upper graph.

6. For the US, the ratio between total public transportation and household expenditure on public transportation is 23.7 pass-km/$. For MX and CL, the same ratio has been assumed to apply, even though the ratio for the UK is slightly less (16.5 pass-km/$) and the ratio for CZ is considerably greater (58.6 pass-km/$).

Several conclusions can be drawn from Fig. 14. The first is that, if the US was to reduce its total energy consumption for transportation to the allocation of 2.8 BOE/person/year, it would have to substantially reduce, not only its household consumption (currently ~8.5 BOE/person/year), but also its non-household consumption (currently ~6.9 BOE/person/year). The reduction in household consumption would affect households directly, but the reduction in non-household consumption would also have an indirect impact, since it provides for the movement of goods and pro-

Table 8
Energy consumption for transportation, population density, and development indicators, for selected countries. UK is United Kingdom, CZ is Czech Republic, HU is Hungary, MX is Mexico, AR is Argentina and CL is Chile. The under-five mortality rate is the number of newborn babies expected to die before reaching five years of age. The total fertility rate is the number of children the average woman will have by the end of her reproductive years. The gross enrollment ratio for secondary education is the number of persons enrolled in secondary education as a percentage of the number of persons of secondary school age [42]. The ratio of wealth between rich and poor is the income (expenditure) of the wealthiest quintile of the population divided by the income (expenditure) of the poorest quintile of the population

Country	US	UK	CZ	HU	MX	AR	CL
Energy consumption for transportation (BOE/person/year)	15.4[a]	7.5[a]	3.3[b]	2.7[b]	2.66[a]	2.95[a]	2.7[a]
Population density (persons/km^2)[c]	29	245	130	108	50	13	20
Percentage of population which is undernourished[d]			~2%	~1%	5%	~1%	4%
Under-five mortality rate (per 1000 newborn babies) [41]	8	6	5	10	36	22	12
Total fertility rate [29]	2.0	1.7	1.4	1.4	2.8	2.6	2.4
Gross enrollment ratio for secondary education[e]	97%	129%	99%	98%	64%	77%	75%
Ratio of wealth between rich and poor [41]	8.9	6.5	3.5	3.4	14.2		18.2

[a] See footnote 49.

[b] These figures have been taken from [40] and then scaled by a factor of 1.3, the reason for the scaling being that the values for transportation energy consumption in [40] differ from those in footnote 49, the value for the UK in [40] being less than that in footnote 49 by a factor of 1.3.

[c] See footnote 35.

[d] The State of Food Insecurity in the World, 4th ed. Food and Agriculture Organization of the United Nations, 2002, ISBN 92-5-104815-0 (http://www.fao.org/DOCREP/005/Y7352e/Y7352e00.HTM).

[e] Note that the secondary school age is ~12 years (depending on country) to 17 years, and that the persons enrolled can include mature students enrolled for vocational training, etc. (which is why the UK figure exceeds 100%). The data is from [42].

Table 9
Transportation profiles for the countries in Table 8. Household consumptions/expenditures are approximations to the total consumption/expenditure by all households, divided by national population. The total jet fuel consumption is the total jet fuel consumed, divided by national population. Public transportation means bus, rail and urban mass transit. The total public transportation is the total passenger-km performed by these modes divided by national population

Country	US	UK	CZ	HU	MX	AR	CL
Energy consumption for transportation (BOE/person/year)	15.4	7.5	3.3	2.7	2.66	2.95	2.7
Private road vehicles per 1000 people[a]	777[b]	462 [40]	339 [40]	220 [40]	94[c]	134 [44]	83 [44]
Household consumption of motor fuel (barrels/person/year)	7.8[d,e]	2.5[f]	0.84[p]		1.1[c]		1.23[g]
Average number of persons per household	2.5[h]	2.5 [45]	2.7[p]		4.6 [46]		3.84[i]
Household consumption of private road vehicle travel (km/person/year)	19,000[j]						
Total jet fuel consumption (barrels/person/year)	2.3[k]	1.43[l]	0.15[l]	0.14[l]	0.20[l]	0.31[l]	0.32[l]
Household expenditure on airfares ($/person/year)	102[h]	25[f]	1.7[q]		16.1[c]		21.8[m]
Household consumption of jet fuel (barrels/person/year)	0.40[n]						

(*continued on next page*)

Table 9 (*continued*)

Country	US	UK	CZ	HU	MX	AR	CL
Household consumption of air travel (km/person/year)	850[o]						
Household expenditure on public transportation ($/person/year)	42[h]	95[f]	34.5[q]		110[c]		118[m]
Total public transportation (km/person/year)	996[b]	1570 [48]	2020 [40]	2200 [40]			

[a] For the US and UK, private road vehicles means all two axle, four tyre vehicles plus motorcycles (all regardless of owner). For MX, AR and CL, motorcycles are excluded. For CZ and HU, only passenger cars are included. However, in the case of the UK, passenger cars constituted 90% of the total, so the numbers are expected to be useful for comparison, despite the slightly different definitions.

[b] National Transportation Statistics 2001, BTS02-06, [3], U.S. Government Printing Office, Washington, DC, July 2002 (http://www.bts.gov/publications/nts/index.html).

[c] North American Transportation in Figures, BTS00-05, see footnote 1 (http://www.bts.gov/itt/natf/natftab.html).

[d] Transportation Statistics Annual Report 2000, BTS01-02, see footnote 1 (http://www.bts.gov/publications/tsar/2000/index.html).

[e] See Table 3, footnote b and above, footnote d.

[f] Using household expenditure data from [45], petrol and diesel prices from Quarterly Energy Prices, United Kingdom Department of Trade and Industry (http://www.dti.gov.uk/energy/inform/energy_prices/), and exchange rate data from footnote r, as required.

[g] Using footnote i and assuming a price for petrol of 170 Chilean pesos per litre—see Encuesta Nacional Industrial Anual 1996 (http://www.ine.cl/chile_cifras/pdf/enia96.pdf).

[h] See Table 3 footnote b.

[i] Quinta encuesta de presupuestos familiares (Agosto 1996—Julio 1997), Instituto Nacional de Estadisticas, Chile (http://w.ine.cl/vencuesta/entrada.htm). Note that the survey was restricted to the Gran Santiago area, but that this still encompassed 36% of the Chilean population.

[j] This has been obtained from the average household vehicle usage of 18,500 vehicle-miles per household per year, see footnote d above, and an average vehicle occupancy of 1.6, [47].

[k] See footnote 10.

[l] Country energy balances, year 1999, Energy Information Administration, US Department of Energy (see, for example, http://www.eia.doe.gov/emeu/world/country/cntry_UK.html).

[m] Using footnote i and assuming an exchange rate of 410 Chilean pesos per US dollar[r].

[n] In 1997, fuel represented 11% of the total operating costs of the US major and national carriers [47]. So, from $102 expended on airfares, ~$11 would be for purchase of fuel. Assuming fuel costs $0.65 per gallon (see Fig. 5), $11 purchases 16.9 gallons (0.40 barrels).

[o] 0.40 barrels of kerosene has an energy content of 2.2 GJ (see Table 1), which is 2.1 million Btu, and, in 1997, US certified air carriers had an average energy intensity of 4,000 Btu per passenger-mile (see footnote 50.)

[p] Czech Statistical Office (http://www.czso.cz/eng/angl.htm).

[q] Using footnote p and exchange rate data from footnote r.

[r] U.S. Department of Commerce (http://ia.ita.doc.gov/exchange/).

vision of services, many of which are ultimately destined for household consumers. US citizens would therefore experience a significant reduction in living standard, which would extend well beyond the loss of household transportation. To a lesser extent, the same applies to the UK.

The second conclusion is that, in MX and CL, the energy available for household transportation is ~2 BOE/person/year. 2 BOE would therefore seem a reasonable estimate for the maximum amount of energy a person could use for household transportation in a year, while remaining faithful to the humanitarian and environmental objectives outlined in Appendix G. If used exclusively for air travel, 2 BOE yields ~4800 km of travel (see footnote 50). If used exclusively for private road vehicle travel, and assuming US conditions, 2 BOE yields ~5100 km of travel (see footnote 50). Since the US vehicle fleet is not particularly fuel efficient, and car occupancy in the US is not particularly high (1.6 persons per car, on average [47]), it might be possible to increase the latter figure using existing technology and/or organizational measures. However, it is unlikely that work related travel would add significantly to the total travel of any citizen, since the household consumption of 2 BOE/person/year already accounts for more than 70% of the 2.8 BOE/person/year allocated for all transportation.

Given these conclusions, a guideline which could be given to consumers, which is both simple and reasonable, is that, if they wish to act in accordance with the humanitarian and environmental objectives outlined in Appendix G, then they should limit their own travel (excluding walking, bicycling, etc.) to, on average, less than 8000 km per year (150 km per week).

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